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Bench-Scale Evaluation of Non-U.S. Coals for NOx Formation Under Excess Air and Staged Combustion Conditions

Energy and Environmental Research Corp.
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Industrial Environmental Research Lab.
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by

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ABSTRACT

The report describes results of bench-scale fuel-screening experiments. Twenty non-U.S. coals (including lignite, subbituminous, and bituminous) were tested in a 21 kWt refractory-lined tunnel furnace. NO_x emissions were measured as a function of coal composition and initial fuel/air contacting rate under excess air conditions. In addition, in-flame measurements were made to quantify the influence of stoichiometry and temperature on the fate of fuel nitrogen species under staged combustion conditions. The results show that NO_x emissions are generally correlated to fuel nitrogen content; however, factors such as hydrocarbon volatile content and the partition of fuel nitrogen between char and volatile fractions were also important. Moreover, coals with high volatile contents give high NO_x emissions under well mixed or excess air conditions, but give low NO_x emissions under staged conditions or with long axial flames. Both increasing flame temperature and decreasing particle size decrease NO_x emissions in staged combustion, but increase in well mixed combustion. Increasing the rate of heat extraction from staged combustion, however, generally reduces NO_x emissions via a complex mechanism.

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1.0 INTRODUCTION

1.1 Background - NO_x Formation

During the combustion of coal, nitrogen oxides (NO_x) are formed by at least two fundamentally different chemical mechanisms: high temperature fixation of atmospheric nitrogen (leading to thermal NO_x), and the oxidation of nitrogen chemically bound in the fuel (leading to fuel NO_x). The formation of thermal NO_x in gas systems has been studied extensively and is usually described using a modified Zeldovich mechanism.

At least 70 percent of the nitrogen oxides formed during the combustion of pulverized coal are due to the oxidation of coal-bound nitrogen. Therefore, it is of major importance in the development of low emission systems to understand the phenomena which control the fate of this fuel-bound nitrogen. The current hypothesis concerning the fate of coal nitrogen during pulverized coal combustion can be simplified to include the following three processes:

- Thermal Decomposition. As the coal particle is heated, it decomposes. Volatiles are evolved, and the nitrogen is split between the volatile and solid fractions. The nitrogen remaining in the solid, char nitrogen, is a function of the temperature attained by the particle and the time at that temperature.

- Gas Phase Reactions. The gas phase nitrogen which is produced from the volatile coal fractions can react to form NO, NH_3, HCN or N_2. The formation of NO is favored under fuel lean conditions and the formation of N_2 is favored under fuel rich conditions.

- Char Burnout. The char nitrogen which is associated with the solid, either as a pyrolysis product of tars or as the original coal char, can also be oxidized to form NO during char burnout. Char nitrogen conversion efficiency is usually assumed to be low.

This simplified hypothesis provides a basis to understand the potential fuel effects involved in NO formation during pulverized coal combustion as well as recognizing the steps involved in the optimization of a staged combustion system.

1.2 Control Technology

Most NO_x control technology is based on the use of combustion modification techniques because they have proven cost-effective compared to stack gas scrubbing. The most successful combustion modification technique for coal has been staged combustion - either through external staging (biased firing, overfire air ports, off-stoichiometric combustion), burner modifications (staging via delayed mixing) or compartmentalization (primary combustion furnace). In all of the concepts a portion of the combustion air is removed from the normal burner air and added at some distance downstream. Field testing and pilot-scale studies have demonstrated the potential of external staged combustion.

During the past 10 years, the U.S. Environmental Protection Agency has devoted a considerable resource to the understanding of the mechanisms involved in the formation of nitrogen oxides (NO_x) during the combustion of pulverized coal. This understanding has led to the development of a low NO_x pulverized coal burner (the Distributed Mixing Burner, DMB) which is suitable for retrofit to coal fired boilers. The EPA DMB uses a combination of proper fuel injector and distributed air addition to create conditions which minimize fuel NO production and yet provide a combined heat-release zone which is compatible with current boiler combustion chambers.

1.3 Purpose and Scope

One of the problems associated with the application of the Distributed Mixing Burner in coal fired boilers is the impact of the fuel type upon burner performance. In this instance, performance not only refers to pollutant emissions but also to ignition stability, combustion efficiency, and the necessity to re-optimize the burnout to take account of differences in coal properties.

The purpose of this program is to assess the application of low NO_x coal combustion technology to non-U.S. coals. The overall objectives are to define the level of NO_x control likely to be achieved with non-U.S. coals and to determine the performance of the Distributed Mixing Burner on non-U.S. coals. The overall effort consists of bench-scale fuel screening studies and pilot-scale burner evaluation. The goals of the bench-scale investigation are to

determine the NO_x formation characteristics on non-U.S. coals under both excess air and staged combustion conditions, and to provide a basis for comparison with U.S. coals and for the selection of fuels to be tested in the pilot-scale investigations.

This report describes the results from the bench-scale fuel screening experiments. Twenty non-U.S. coals (including lignite, subbituminous and bituminous) were tested in a 21-kw_t refractory-lined tunnel furnace. NO emissions were measured as a function of coal composition and initial fuel/air contacting rate under excess air conditions. In addition, in-flame measurements were made to quantify the influence of stoichiometry and temperature on the fate of fuel nitrogen species under staged combustion conditions.

2.0 EXPERIMENTAL FACILITIES

2.1 Bench-Scale Reactor

The experimental reactor, illustrated in Figure 1, is a refractory-lined, down-fired tunnel which consists of six separate sections. Each section is made up of an outer steel shell and three layers of refractory insulation. The main combustion chamber is 15.2 cm in diameter. The furnace entry (top section) consists of a 30.5 cm long refractory quarl that diverges gradually from 5.1 cm to the full 15.2 cm diameter. The long quarl helps to eliminate recirculation and improves the one-dimensionality of the flow field. Sampling or air/additive injection can be achieved through the access ports located at different axial positions.

All of the experiments for the excess air screening studies were conducted with the straight tunnel configuration shown in Figure 1. During the latter phases of the program, the top four sections of the furnace were modified to facilitate the measurement of in-flame species concentrations and to permit the investigation of the effects of heat extraction under staged combustion conditions. The modified furnace sections, as shown in Figure 2, include:

1. A removable radiation shield upstream of the staging/cooling position to minimize the effects of downstream parameters upon upstream conditions.
2. Two refractory sections with removable coils to allow cooling of first and/or second stage combustion products.
3. A removable staging choke to ensure isolation of the first stage.
4. A removable air ring for second stage air injection.

2.2 Bench-Scale Burners

Pulverized coal supplied from a twin screw feeder is transported by primary air to the burner on top of the furnace. Figure 3 shows the burners used in this study. They are of two basic types: a premixed and a diffusion burner. In the premixed burner, primary air and the pulverized coal are injected radially outward through six 0.32 cm holes (at a 30° angle with the vertical) into a premixing chamber. The preheated main combustion air is

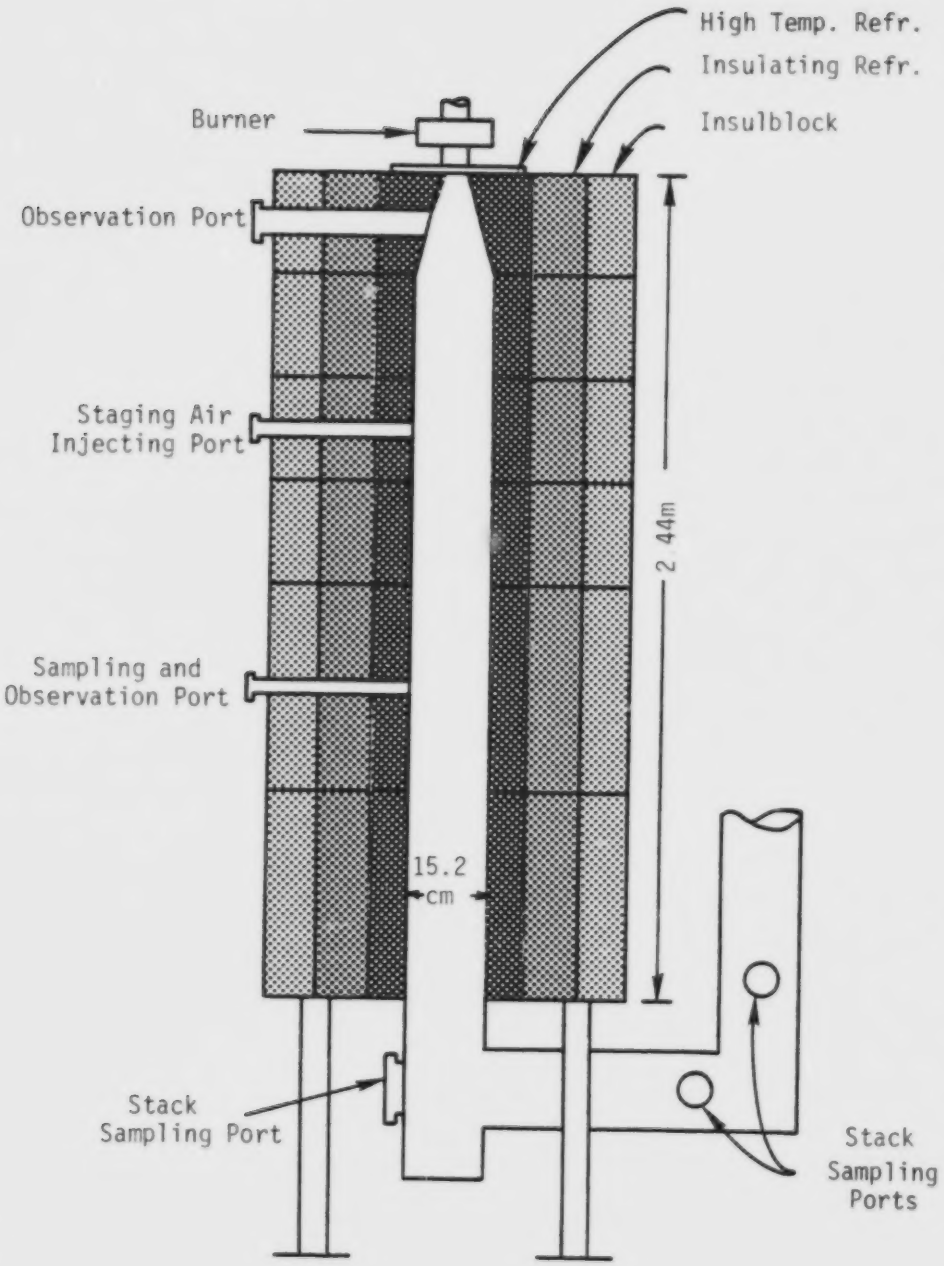

Figure 1. Bench-Scale Reactor.

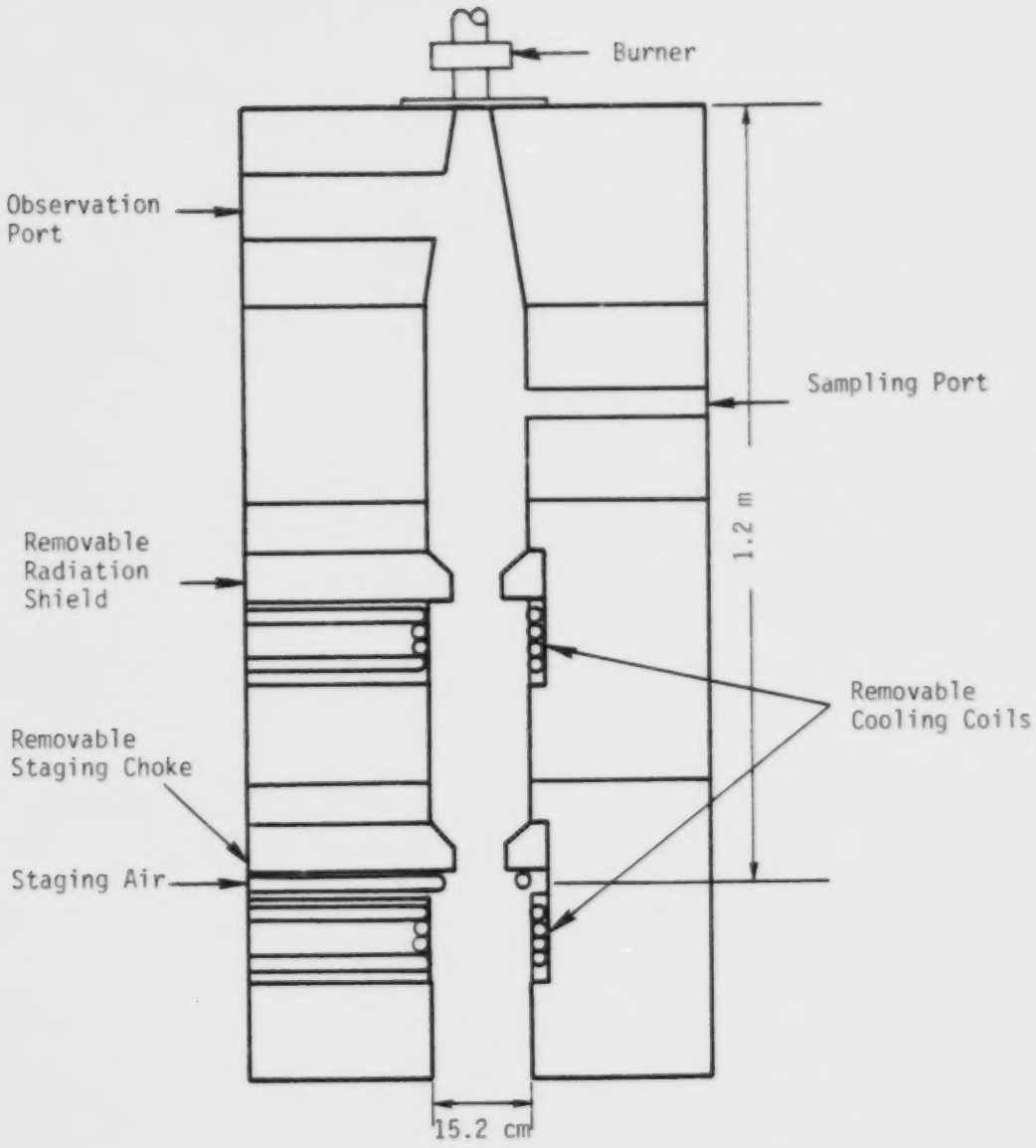

Figure 2. Modified Furnace Sections for Staged Combustion Studies.

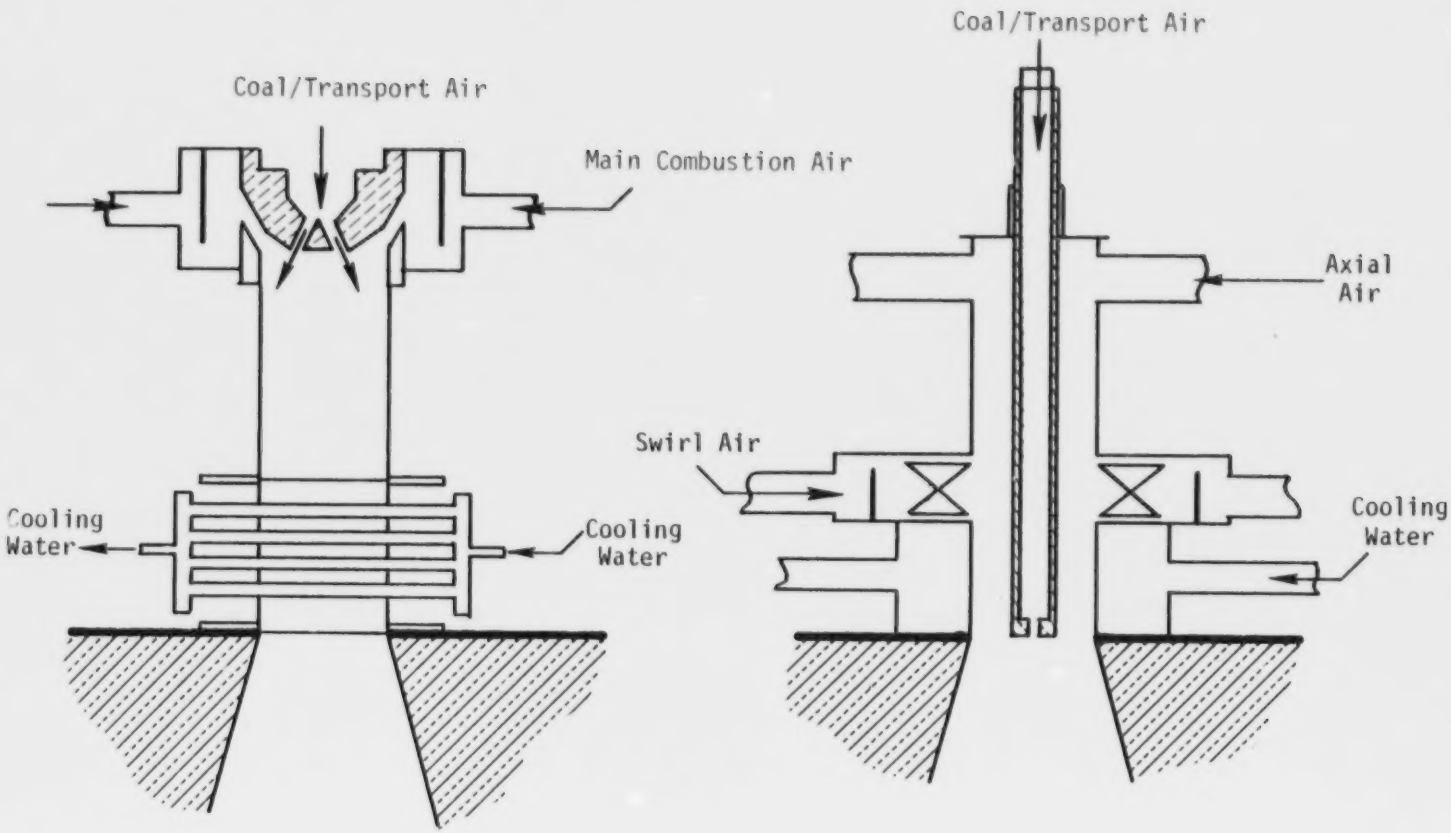

Figure 3. Bench-Scale Burners.

injected radially inward into the chamber in six round jets opposing the coal jets. This burner produces predominantly one-dimensional flow with negligible backmixing. Ignition in the mixing chamber is prevented by a series of water-cooled tubes which separates the mixing chamber from the hot furnace.

The coal plus transport air can also be supplied to the diffusion burner where variable swirl is achieved by dividing the main combustion air into two streams: one which flows axially, parallel to the injector, and the other which flows through swirl vanes (see Figure 3). Swirling all the combustion air and injecting the coal-plus-transport-air through a 1.9 cm O.D. injector with six 0.48 cm diameter holes spaced radially at the tip produces a short, intensely backmixed flame. Conversely, an axial diffusion flame is obtained with a single hole, parallel injector (1.12 cm diameter hole). In the axial mode, the combustion air is also added through swirl vanes to provide a stable ignition zone at the injector.

2.3 Measurement Systems and Analytical Methods

Flue gas sampling was conducted with a stainless steel water cooled probe (jacketed with cooling water) and the following gas species were measured continuously by the method indicated:

- NO - chemiluminescence
- O_2 - paramagnetism
- CO/CO_2 - nondispersive infrared

In-flame gas samples were taken with a water spray probe as shown in Figure 4. The probe is made of four concentric stainless steel tubes. The outside diameter of the probe is 3.2 cm and the sample flow passage is 1.26 cm in diameter. Water spray at the tip of the probe provides rapid quenching of the oncoming combustion products. The sample train for in-flame measurements is shown in Figure 5. Samples could be directed to either side of the system, i.e., dry measurements of NO, CO/CO_2 and O_2 species or wet measurements of NH_3 and HCN species. Gas phase HCN and NH_3 species were collected in a gas washing unit which consists of an impinger in series with a bubbler containing a fritted glass cylinder. The sample solutions were subsequently analyzed for CN and dissolved ammonia using specific ion electrodes.

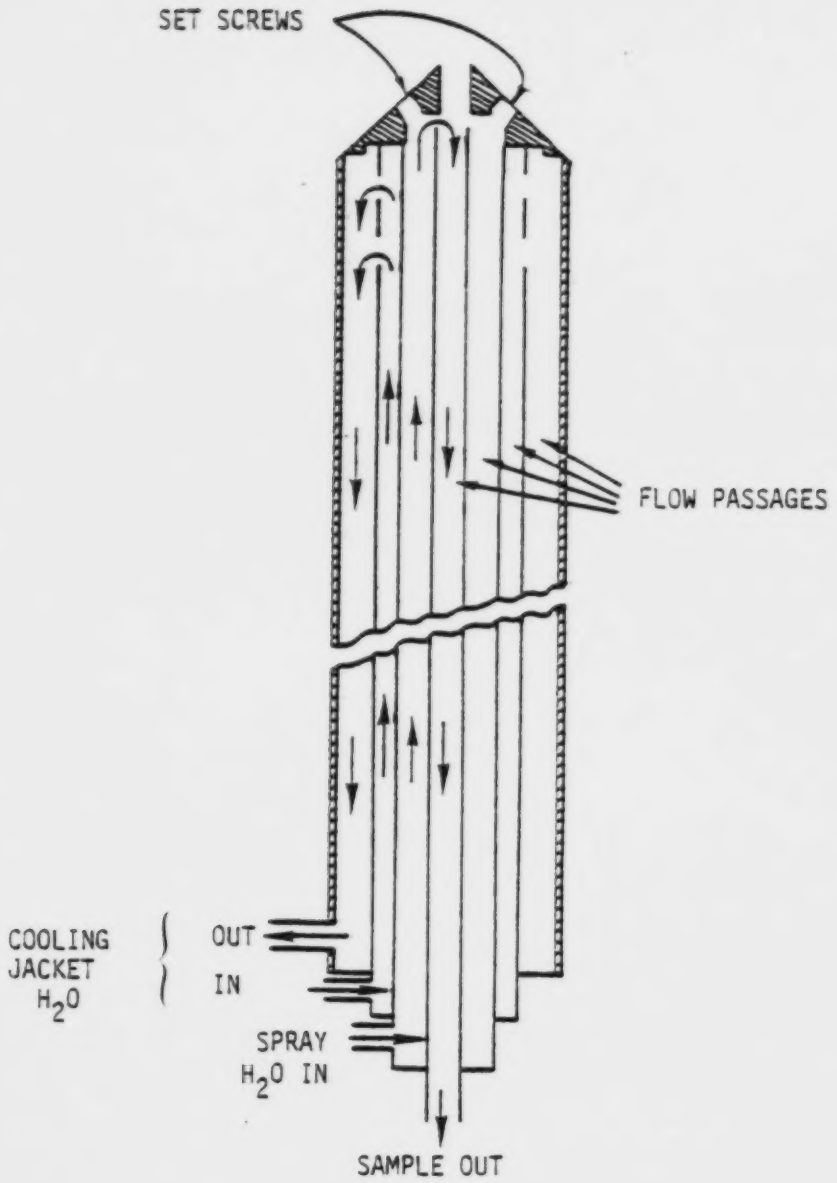

Figure 4. Schematic of Water-Spray Probe.

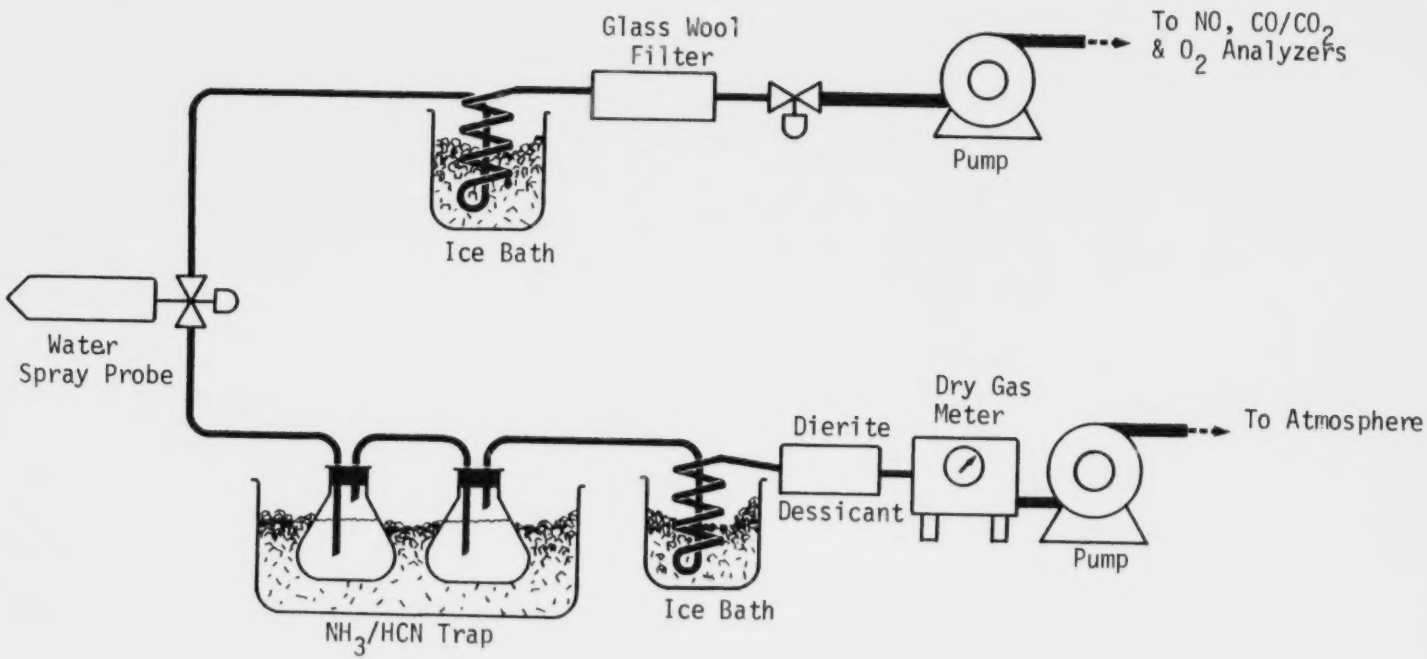

Figure 5. Sample Train for In-Flame Measurements.

An elbow shaped water quench probe was used for collecting in-flame solid samples isokinetically. This probe is similar to the one shown in Figure 4 except that the water cooling jacket has been replaced with a layer of insulating ceramic fiber which minimizes thermal disturbances resulting from the cooling probe. The collected solid samples were analyzed for C, H, N and ash content with a Perkin-Elmer elemental analyzer.

3.0 FUELS

All the coals were pulverized to 65 percent through 200 mesh (U.S. standard sieve, 74 micron) for the fuel screening studies. The properties of these non-U.S. coals are listed in Table 1. Figure 6 shows the nitrogen content as a function of coal rank for both the non-U.S. coals (solid symbols) and the U.S. coals (open symbols). The majority of the coals investigated have nitrogen contents ranging from 1.0 to 2.0 percent, on a dry ash-free (DAF) basis. The non-U.S. coals contain a wider range of nitrogen than the U.S. coals. The properties of U.S. coals are listed in Appendix E.

Table 1. Fuel Analysis

Fuel Symbol	◆	■	◢	◣	●	⬢	⬢	◤	✚
Fuel Designation	A	B	C	D	E	F	G	H	I
Proximate Analysis (as received)									
Moisture	30.07	27.05	13.84	6.62	1.03	3.62	0.87	1.88	2.09
Ash	14.27	9.69	15.12	11.18	18.51	10.73	6.94	16.10	18.19
Volatile Matter	28.19	29.59	32.58	33.52	30.26	34.53	34.10	19.72	28.38
Fixed Carbon	27.47	33.67	38.46	48.68	50.20	51.12	58.09	62.30	51.34
Ultimate Analysis (dry)									
Carbon	54.55	59.33	57.83	67.93	67.31	71.21	78.80	71.57	68.45
Hydrogen	3.03	3.82	3.76	4.21	4.85	4.73	5.26	3.98	4.34
Nitrogen	0.64	1.06	1.28	0.94	1.42	1.19	1.68	0.96	2.00
Sulfur	0.93	0.42	0.59	0.27	2.37	1.20	1.88	0.27	0.59
Ash	20.41	13.28	17.55	11.97	18.71	11.13	7.00	16.41	18.58
Oxygen	21.50	21.49	18.99	14.68	5.34	10.54	5.38	6.81	6.04
Heading Value									
Btu/lb	6,107	7,488	8,256	10,811	11,862	11,882	14,000	11,839	11,597
Kcal/Kg	3,393	4,160	4,587	6,006	6,590	6,601	7,778	6,577	6,443
Classification (ASTM D388)	Lignite A	Sub-Bituminous C	Sub-Bituminous B	High Volatile C Bituminous	High Volatile A Bituminous	High Volatile B Bituminous	High Volatile A Bituminous	Medium Volatile Bituminous	High Volatile A Bituminous

Table 1. (Cont'd)

Fuel Symbol	▲	▼	▶	▲	▼	◆	◀	●	▼	●	◣
Fuel Designation	K	L	M	N	O	P	R	S	T	U	V
Proximate Analysis (as received)											
Moisture	5.24	4.28	5.48	1.58	3.23	3.20	2.12	1.88	2.38	4.51	0.25
Ash	16.82	14.44	10.50	6.37	16.36	16.40	14.99	18.37	16.99	11.29	14.60
Volatile Matter	29.56	29.74	27.30	38.45	26.99	27.46	24.01	24.40	25.95	28.13	20.69
Fixed Carbon	48.38	51.54	56.72	53.60	53.42	52.94	58.88	55.35	54.68	56.07	64.46
Ultimate Analysis (dry)											
Carbon	67.34	69.39	74.12	78.74	69.54	66.34	73.47	67.51	69.44	71.93	74.98
Hydrogen	4.10	4.33	4.24	5.63	4.39	3.99	4.32	4.19	4.08	4.75	4.27
Nitrogen	1.19	1.33	0.83	1.69	1.51	1.53	1.43	1.49	1.37	1.64	1.02
Sulfur	0.94	0.86	0.88	1.08	0.68	0.60	1.04	0.50	0.41	0.48	0.20
Ash	17.76	15.09	11.10	6.47	16.90	16.94	15.31	18.73	17.41	11.82	14.64
Oxygen	8.67	9.00	8.83	6.39	6.98	10.60	4.43	7.58	7.29	9.38	4.89
Heating Value											
Btu/lb	10,995	11,394	12,005	13,948	11,719	11,725	12,622	11,938	11,661	11,898	12,920
Kcal/Kg	6,108	6,330	6,669	7,749	6,511	6,514	7,012	6,632	6,478	6,604	7,178
Classification (ASTM D388)	High Volatile B Bituminous	High Volatile B Bituminous	High Volatile B Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	Medium Volatile Bituminous	Medium Volatile Bituminous	Medium Volatile Bituminous	High Volatile B Bituminous	Medium Volatile Bituminous

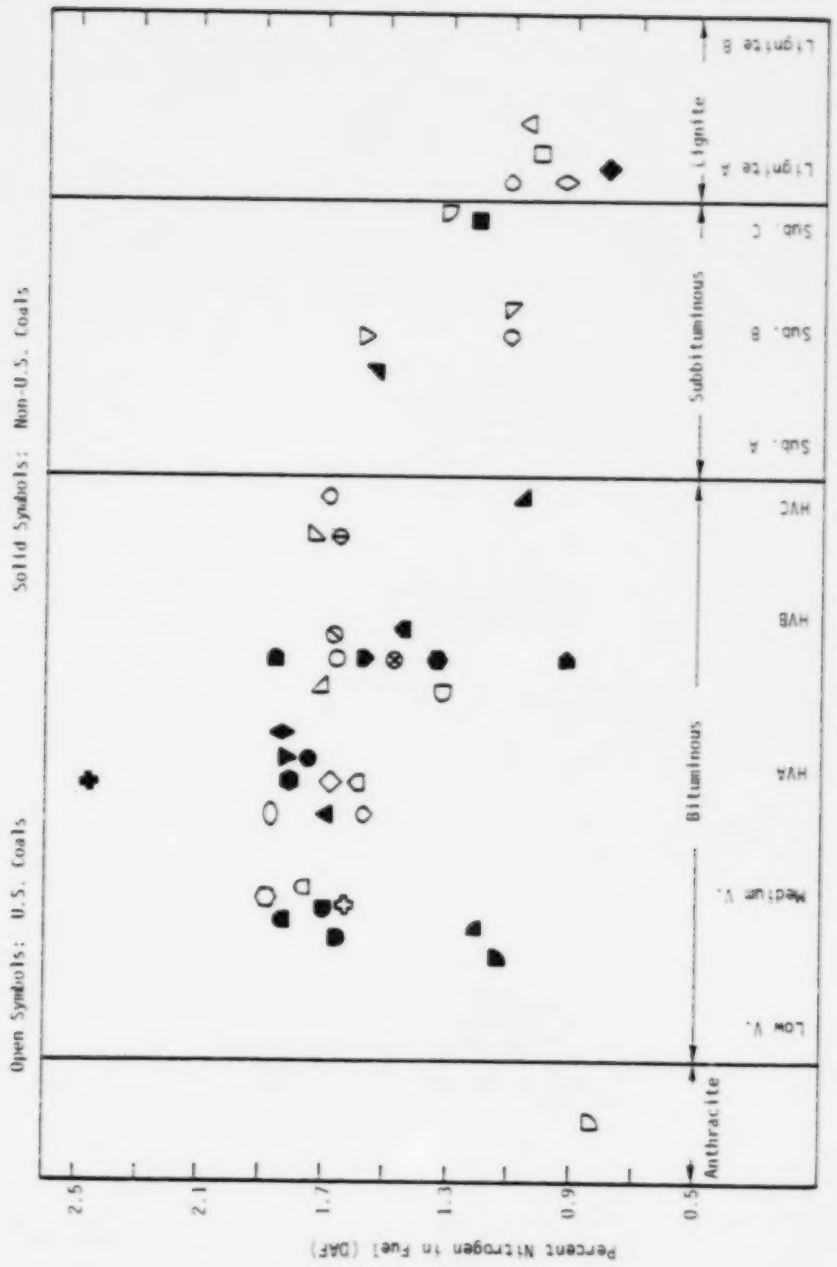

Figure 6. Nitrogen Content as a Function of Coal Rank.

4.0 EXCESS AIR RESULTS

Experiments were carried out to investigate the effects of fuel/air contacting conditions, thermal environment and particle size on NO emissions under excess air conditions. Flue gas sampling was conducted with a stainless steel, water cooled probe and NO concentrations were measured continuously with a chemiluminescent analyzer. These data were obtained at a nominal firing rate of 21 Kw with 550°K secondary air preheat. The unpreheated primary air was maintained at 15 percent of the stoichiometric air requirement. Fuel NO was defined as the emission when molecular nitrogen was excluded from the oxidant, and the fuel was burned in a mixture of 61 percent argon, 18 percent carbon dioxide and 21 percent oxygen.

4.1 Fuel/Air Contacting Conditions

Fuel NO emissions obtained with the premixed burner at 5 percent excess O_2 are summarized in Figure 7 as a function of percent nitrogen in the fuel (dry, ash free) for both the non-U.S. coals and the U.S. coals. The open symbols represent the American coals which include char, anthracite, bituminous, subbituminous and lignite coals. Data obtained with the non-U.S. coals are shown in solid symbols. In general, the non-U.S. coals correlated well with the U.S. coals; fuel NO emissions increased with fuel nitrogen content.

As expected, Coal I (◆) which contained 2.5 percent (DAF) nitrogen gave the highest NO emissions. Likewise, the low nitrogen lignite, Coal B (◆), produced relatively little NO.

However, within any rank there must be fuel properties other than total nitrogen which had a significant impact on fuel nitrogen oxidation. For instance, the two American lignites, Savage (△) and Beulah (□), both have approximately 1.0 percent (DAF) fuel nitrogen, yet their emissions varied by more than 50 percent. Similarly, the two non-U.S. high volatile bituminous coals, Coal P (◆) and Coal N (▲), both have approximately 1.8 percent (DAF) fuel nitrogen and yet they produced significantly different fuel NO emissions. Previous work has suggested that at least part of this difference may be associated with the distribution of the fuel nitrogen within the coal. Nitrogen components which are evolved early in the coal pyrolysis and which produce reactive intermediate species, such as HCN, tend to be oxidized to NO.

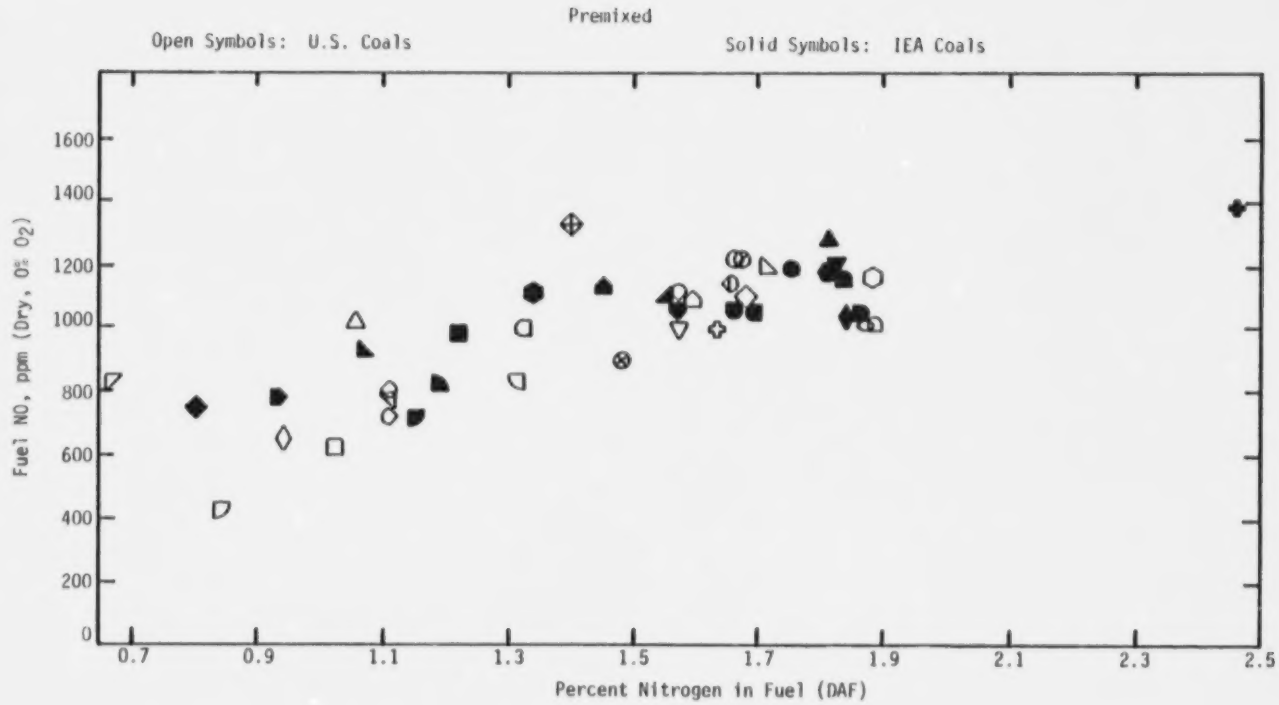

Figure 7. Fuel NO as a Function of Fuel Nitrogen Content.

Alternatively, nitrogen which remains with the solid coal char is less likely to ultimately be oxidized to NO. The medium volatile Coal H (◤) produced significantly lower fuel NO emissions than the corresponding high volatile bituminous coals. This is in direct agreement with the behavior exhibited by the low volatile American anthracite (▽). Thus, it appears that, as with the American coals, it is important to characterize not only the total fuel nitrogen content, but also the distribution of that nitrogen.

Figure 8 shows the percentage fuel nitrogen conversion for these coals as a function of fuel nitrogen content. In general, the fuel nitrogen conversion was in the range of 25 to 45 percent and was not a strong function of total fuel nitrogen content. Significant differences in conversion, especially for the coals with lower nitrogen contents, again indicated that total fuel nitrogen was not the only parameter affecting the conversion of coal nitrogen to NO.

Experiments were also carried out with radial and axial diffusion flame modes to investigate the coupling between fuel properties and fuel/air contacting. These data are shown in Figure 9 and Figure 10, respectively. It can be seen that fuel effects are also significant in radial diffusion flames. Fuel NO emissions from the radial diffusion flames also tended to increase with increasing fuel nitrogen content, whereas there was no obvious dependence of fuel NO on fuel nitrogen content for the axial diffusion flames.

Comparison of the data for the three burner types indicated that the initial premixing of the fuel and air led to the highest conversion of the fuel nitrogen, particularly with high volatile bituminous coals, as illustrated in Figure 11 for a non-U.S. coal, Coal O (▼). (NO emissions as a function of excess O_2 for all the non-U.S. coals tested are presented in Appendix A.) The anthracite (▽) data and the Coal H (◤) data shown in Figure 12 indicated that with low volatile coals initial fuel/air contacting had much less impact on the ultimate formation of fuel NO; emissions were almost identical with all three burner types. These data suggest that a coal which tends to retain its nitrogen in the solid matrix until the char burnout regime will be less amenable to NO_x control via optimized burner design than one which evolves much of its nitrogen early in the pyrolysis process.

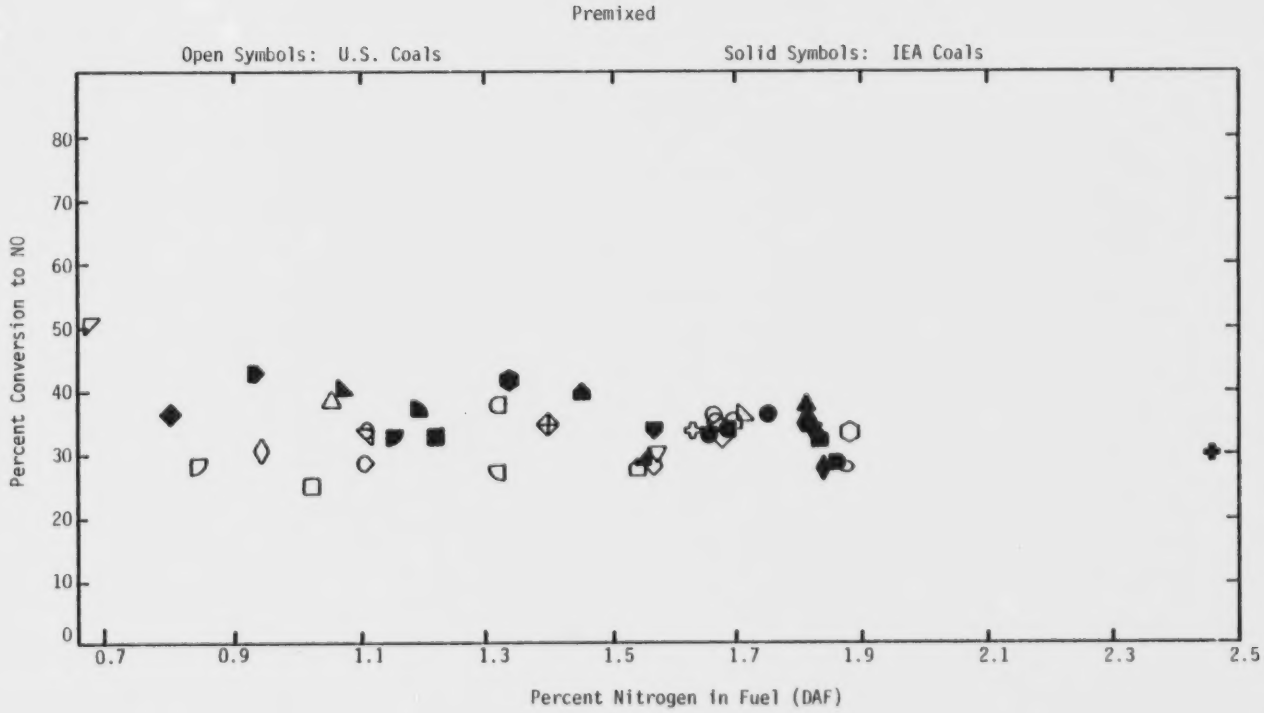

Figure 8. Fuel Nitrogen Conversion in Premixed Flames.

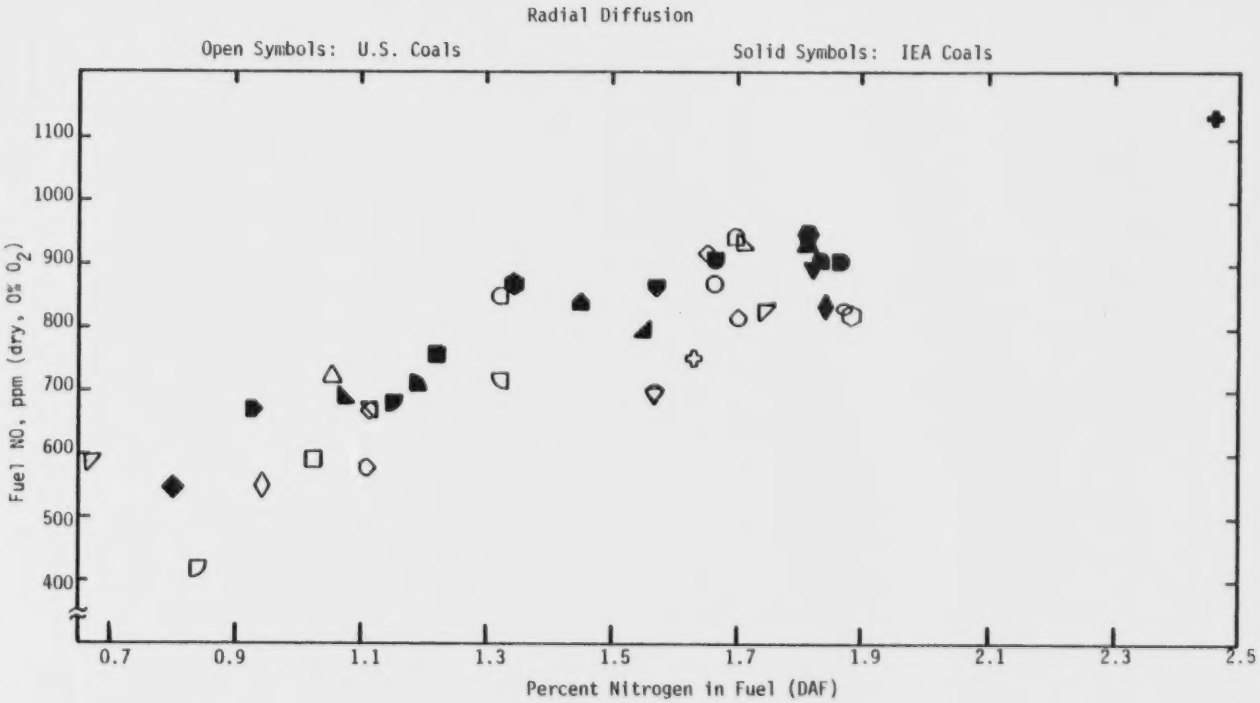

Figure 9. Fuel NO as a Function of Fuel Nitrogen Content.

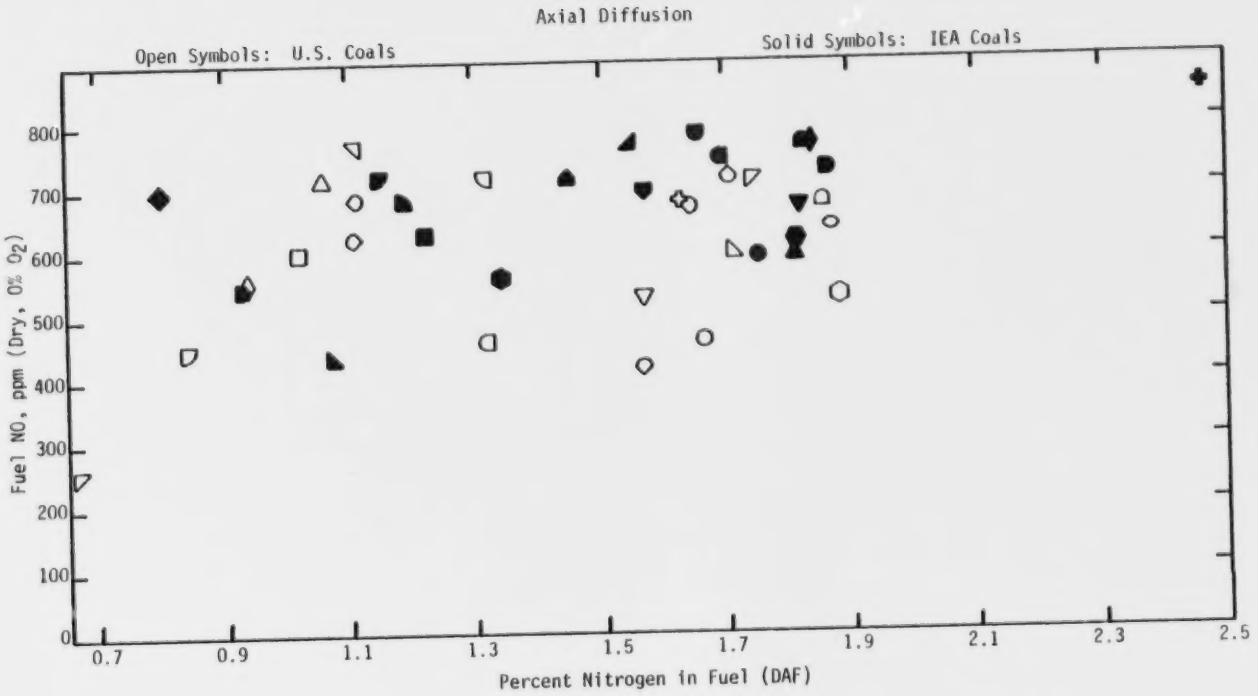

Figure 10. Fuel NO as a Function of Fuel Nitrogen Content.

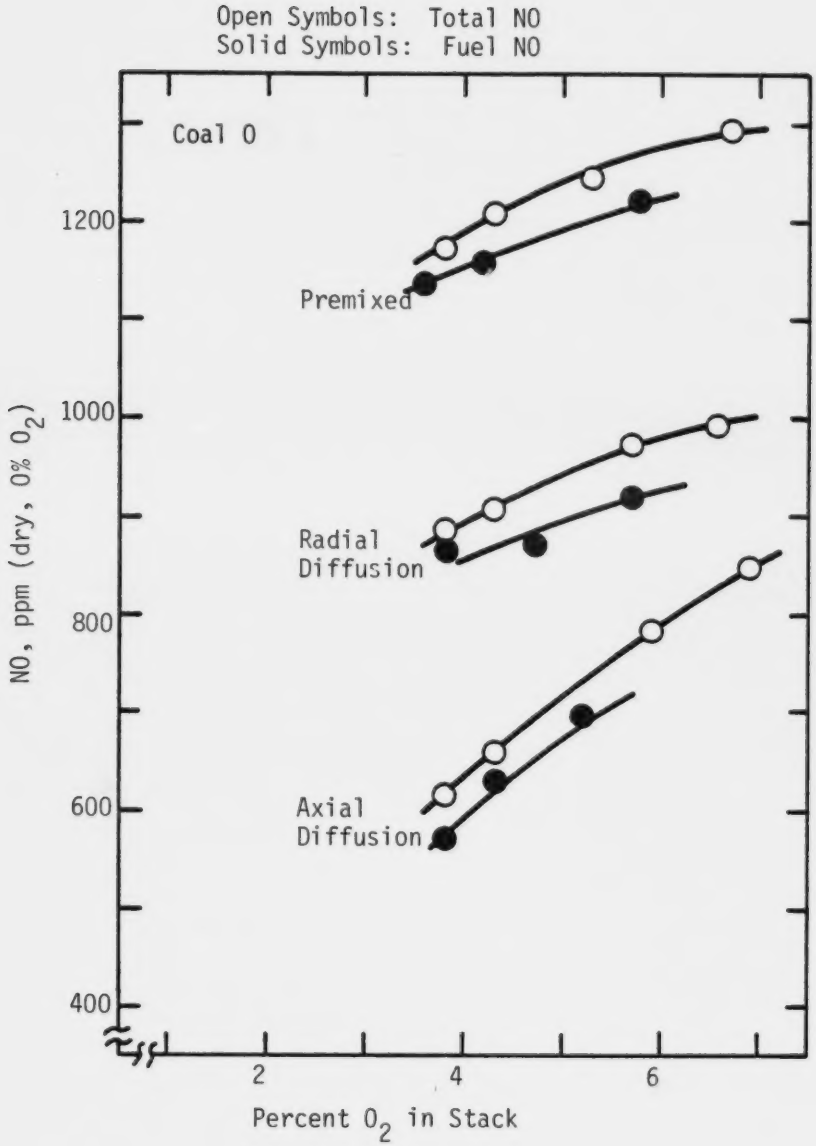

Figure 11. Effects of Fuel/Air Contacting Conditions.

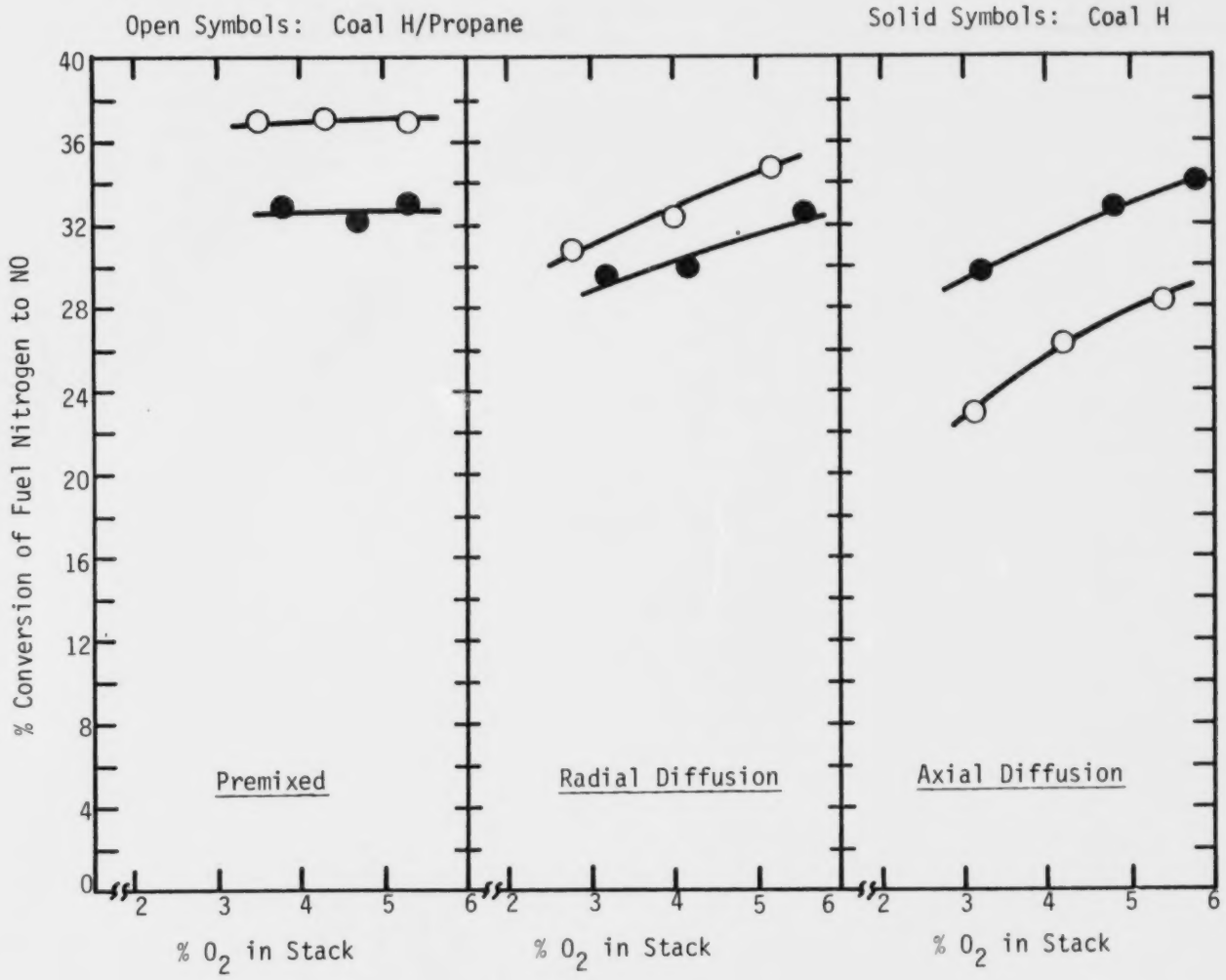

Figure 12. Effects of Hydrocarbon Addition.

Also shown in Figure 12 are the results of propane addition to Coal H (■). Propane was added to the coal feed to raise the total volatile content from 20 percent to 32 percent, with the total firing rate maintained at 21 Kw. Unlike the original coal, this coal/propane mixture exhibited a progressive reduction in emissions from premixed to radial diffusion to axial diffusion. The addition of propane clearly resulted in higher particle temperatures and thus increased the fraction of the volatile nitrogen which was evolved early in the flame and which was, therefore, sensitive to oxygen availability. In the premixed case, early nitrogen evolution is detrimental because of high local oxygen availability; however, in the axial diffusion flame, it is desirable to evolve the fuel nitrogen while the coal is still within the fuel rich flame core.

Observation of the Coal H/propane flame indicated that the addition of propane also helped to stabilize the flame at the fuel injector. In all non-U.S. coals tested with the axial diffusion flame mode, most of the bituminous coals produced stable and attached flames, whereas the flame front of low rank coals and low volatile coals was usually located at some distance from the fuel injector. A series of experiments were therefore carried out by adding propane to those coals which produced detached flames. Stable flames attached to the injector were obtained. NO emissions from these modified flames (with propane addition) and those unmodified, but attached axial diffusion flames were found to increase with increasing fuel nitrogen content, as illustrated in Figure 13. Comparison of Figures 10 (axial flames as found) and 13 (attached axial flames) indicated the strong role of hydrocarbon volatility on fuel nitrogen conversion. The data suggest that the carbon/hydrogen fuel chemistry can alter the combustion stability and thereby influence the local oxygen availability and NO formation.

4.2 Thermal Environment

In these experiments, flame temperature and, therefore, thermal environment was varied by changing the amount of carbon dioxide mixed with the artificial oxidant. Figure 14 shows the influence of thermal environment on fuel NO formation for various fuels in the premixed mode. Although the theoretical flame temperatures shown in parentheses were not the same as the actual local temperatures, they provide a measure of the potential changes in the particle

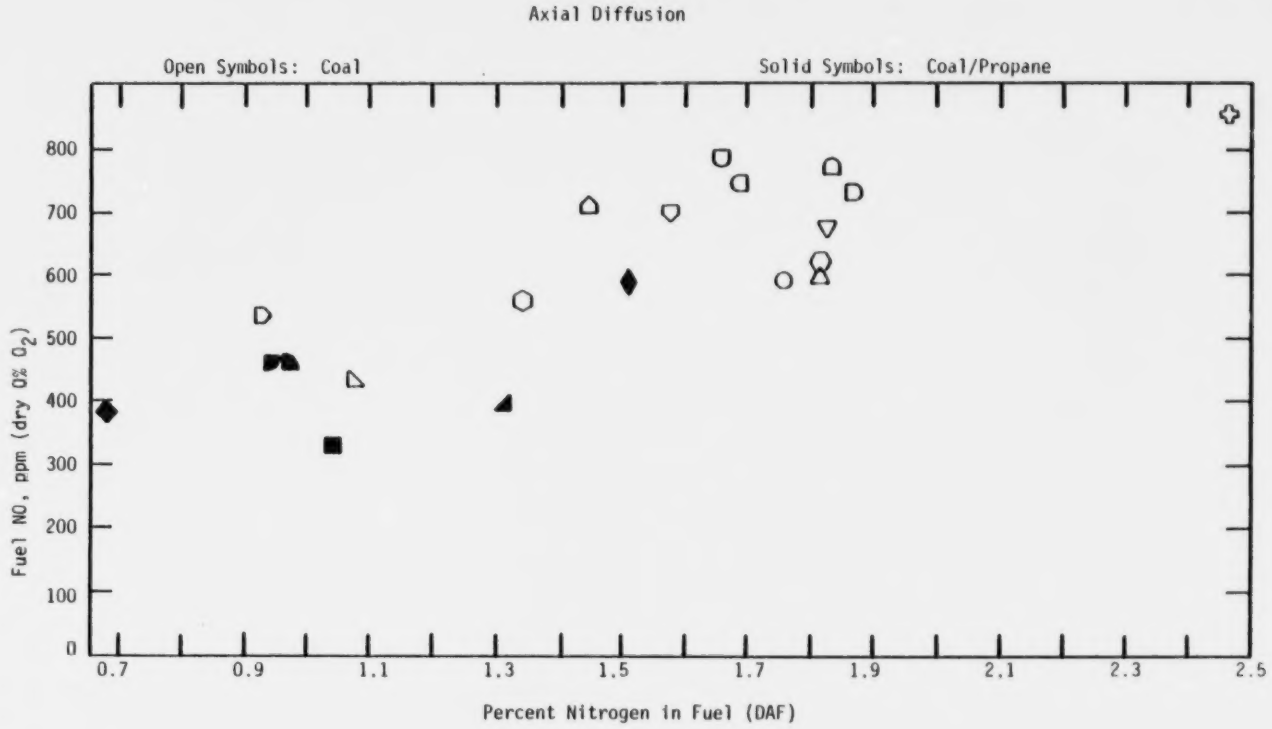

Figure 13. Fuel NO Emissions for Attached Axial Diffusion Flames.

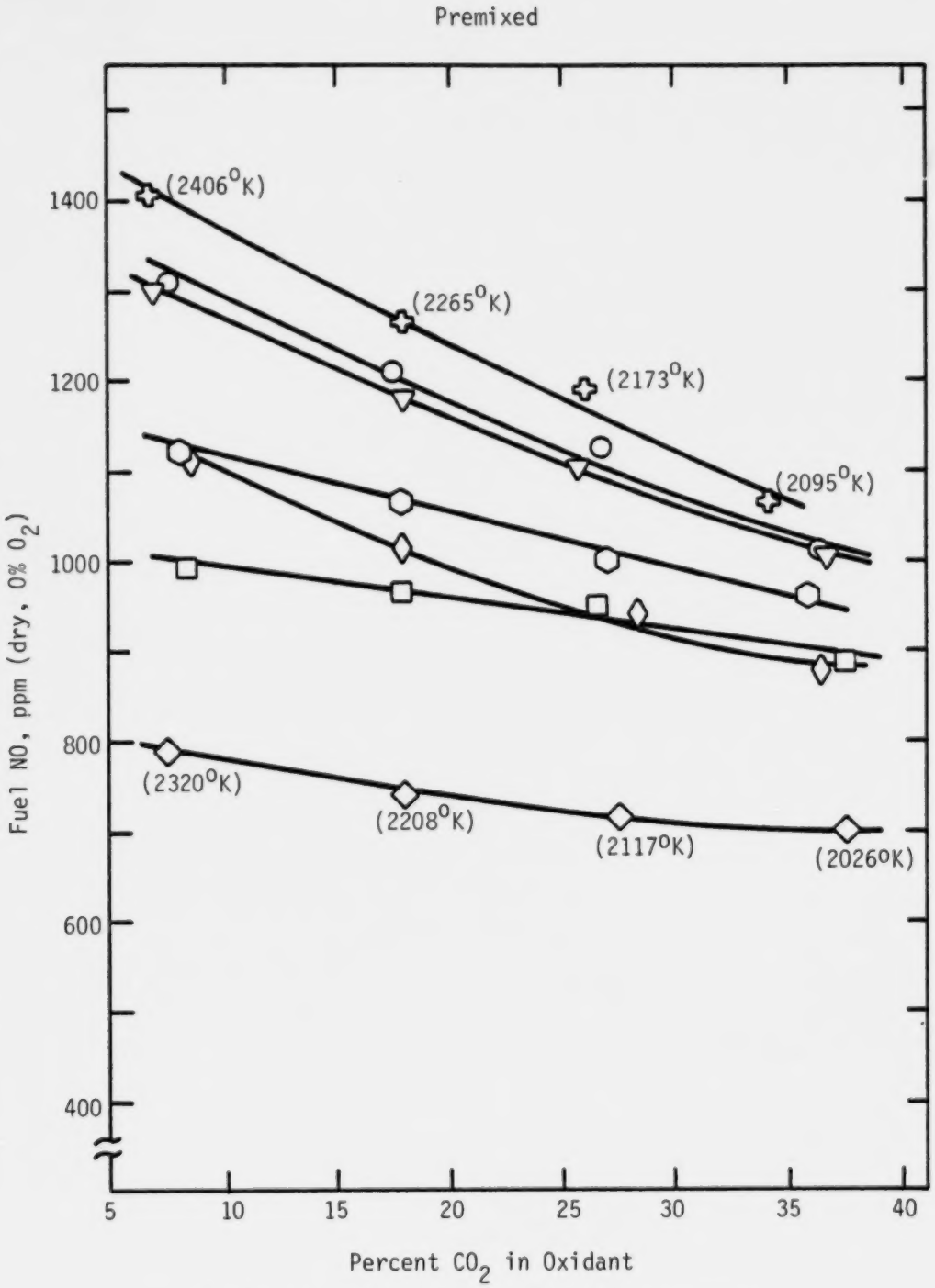

Figure 14. Influence of Thermal Environment.

environment. Fuel NO formation in premixed flames increased with increasing particle temperature. However, the opposite effect was observed with the axial diffusion flames as shown in Figure 15. Fuel NO formation decreased slightly with increasing particle temperature. These trends are consistent with the fuel chemistry effects just discussed. Increasing the particle temperature is undesirable with premixed flames because it increases the evolution of volatile nitrogen in oxygen rich zones. Conversely, with axial flames, the increased evolution occurs within fuel-rich zones and overall conversions are reduced.

4.3 Particle Size

The influence of particle size on fuel NO formation was investigated by burning a high volatile bituminous coal, Coal D (▲), with different size distributions obtained by mechanical sieving. Figure 16 shows the particle size distribution of the various size cuts. The weight-mean particle diameter determined using the Rosin-Rammler distribution is 69 microns for the normal cut, 141 microns for the coarse cut and 39 microns for the fine cut particles. Figure 17 shows the fuel NO emissions resulting from the combustion of these three different size range particles under three different mixing conditions. In premixed flames, the coarse particles produced much lower amounts of fuel NO than the fine particles, whereas in axial diffusion flames fine particles produced lower fuel NO than coarse particles. This can be attributed to differences in volatile and char nitrogen distribution resulting from different particle heating rates and subsequent volatile evolution. (Smaller particles favor increased nitrogen evolution early in the flame front.) Thus, it appears that decreasing particle size increases NO emissions with rapidly mixed flames because it enhances the evolution of fuel nitrogen in an oxygen rich region. Conversely, with axial diffusion flames, decreasing particle size is beneficial because it promotes the evolution of fuel nitrogen within the fuel rich flame core.

4.4 Fuel Properties Correlation

The previous discussions have suggested that fuel NO formation under excess air conditions is highest from those fuels which evolved the most reactive volatile nitrogen and lowest among those coals which tend to retain their nitrogen in the solid phase until the char burnout regime. In an

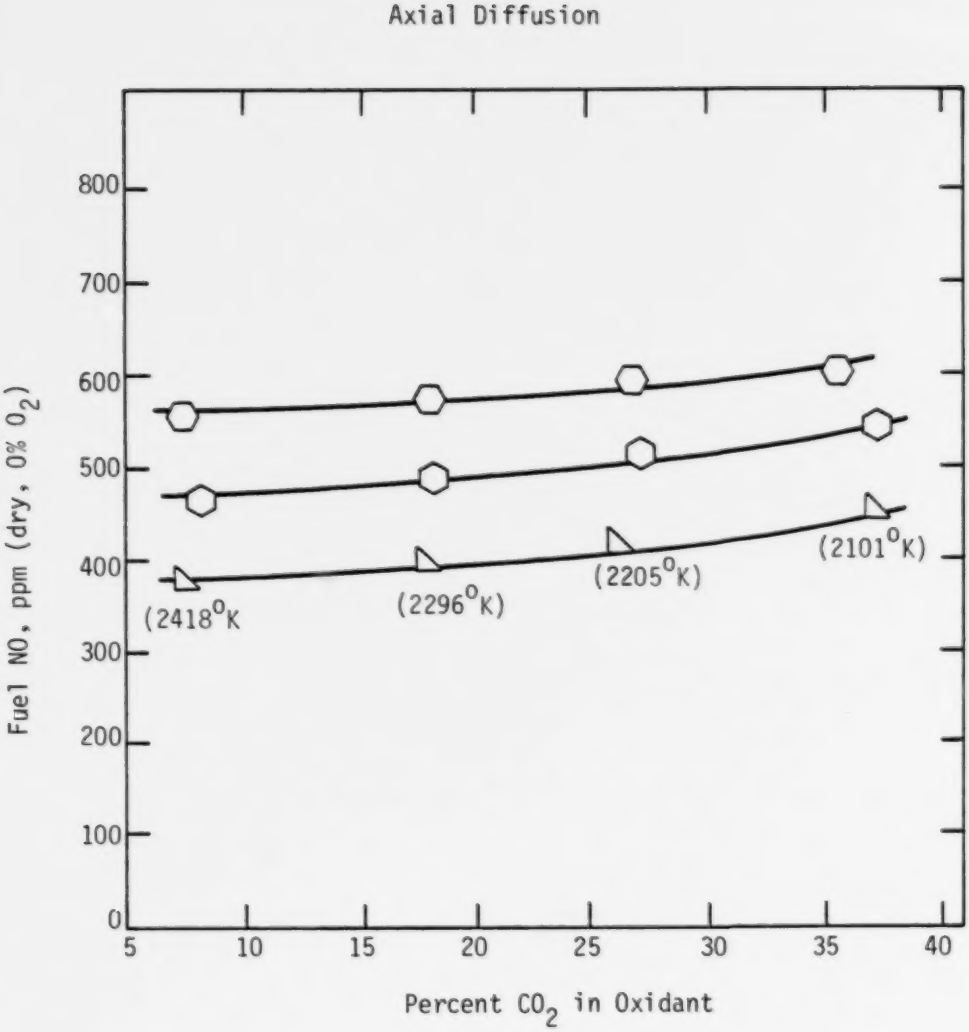

Figure 15. Influence of Thermal Environment.

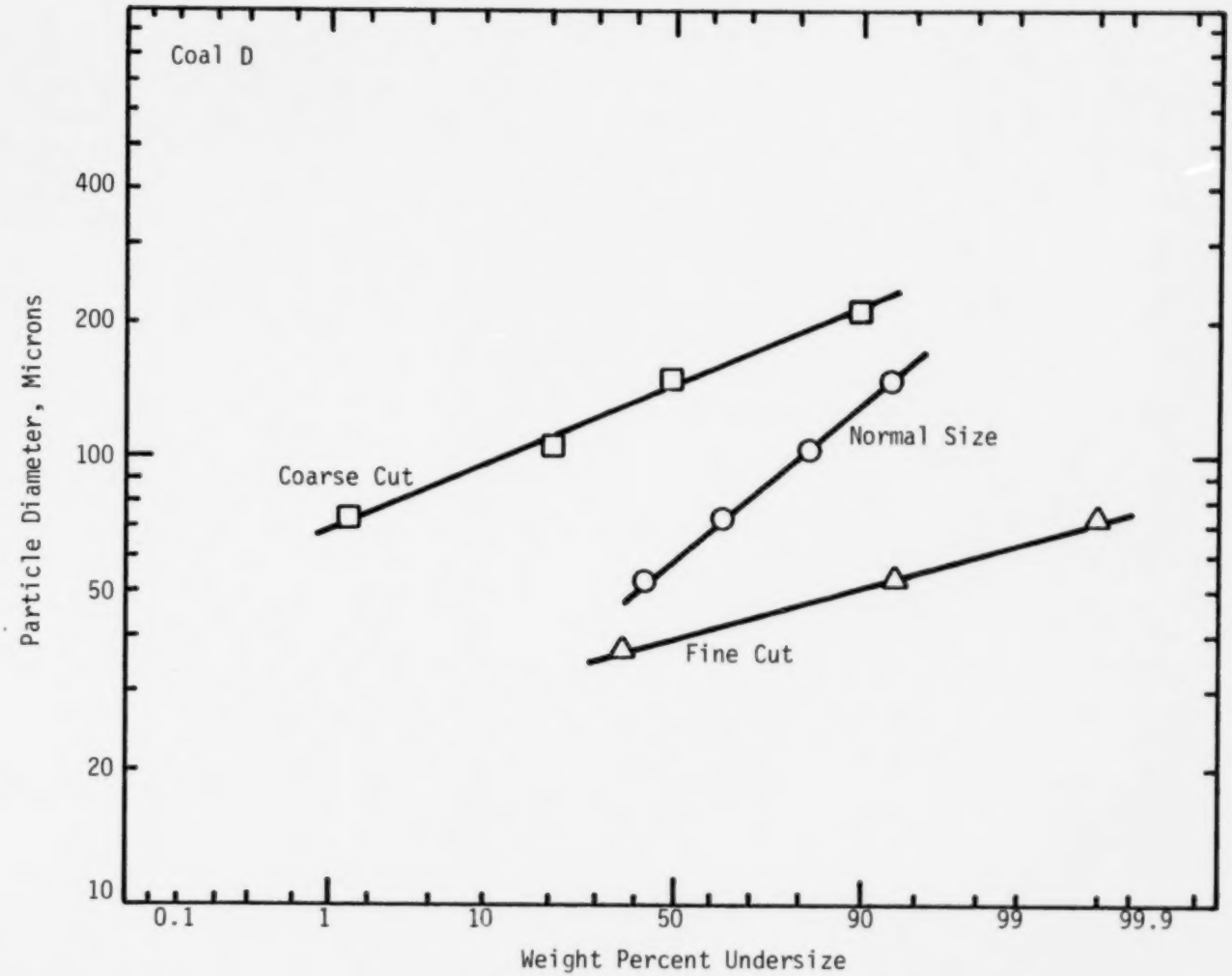

Figure 16. Particle Size Distribution.

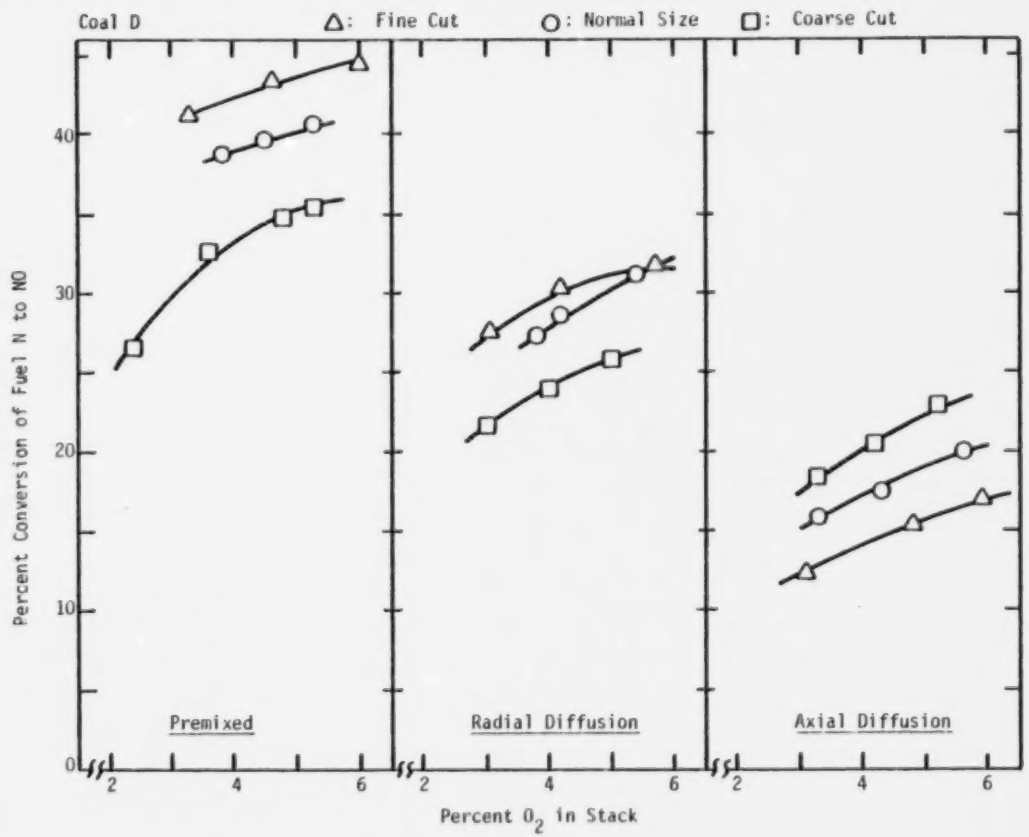

Figure 17. Influence of Particle Size.

attempt to quantify these effects, two types of additional, fundamental fuel property information were obtained. First Soloman and co-workers (Advanced Fuel Research, East Hartford, Conn.) estimated the reactive volatile nitrogen content of IEA coals by pyrolyzing them in vacuum at 1370°K and measuring the HCN yield by FTIR. Secondly, the tendency of each coal to retain nitrogen in the solid phase was characterized by conducting a standard ASTM proximate analysis and subsequently measuring the nitrogen content of the residual char. These data were then used in conjunction with the total nitrogen content of each coal to develop the correlation shown in Figure 18 for the premixed burner. When evaluating the success of this correlation, the reader should remember that the 19 coals shown in Figure 18 represent the most diverse fuels tested throughout the program and range from the 2.5 percent nitrogen, high volatile, bituminous Coal I (✚) to the 0.67 percent nitrogen, pre-dried, Australian, brown coal.

The actual numerical constants in the regression analysis are unimportant because they are clearly a function of the burner system and the time/temperature profile within the furnace. However, the form of the correlation (developed strictly from a multi-variable regression) is consistent with the physical understanding generated through this prgram. The first two terms of the equation represent the mean behavior with respect to the total nitrogen content of the coal. Additionally, coals which produce large amounts of reactive volatile nitrogen tend to give emissions slightly higher than average behavior (the positive third term). Coals which tend to retain large amounts of their nitrogen in the solid phase, tend to give emissions slightly lower than the mean behavior (negative fourth term). These results suggest that if a boiler manufacturer or user has a large data base for the emissions from several different fuels in a particular firing system, it should be possible to approximately predict how a new fuel would operate in that combustion system. Clearly, this type of correlation does not, however, include consideration of changes in emissions which are the direct result of differences in flame stability (e.g., the axial flame data).

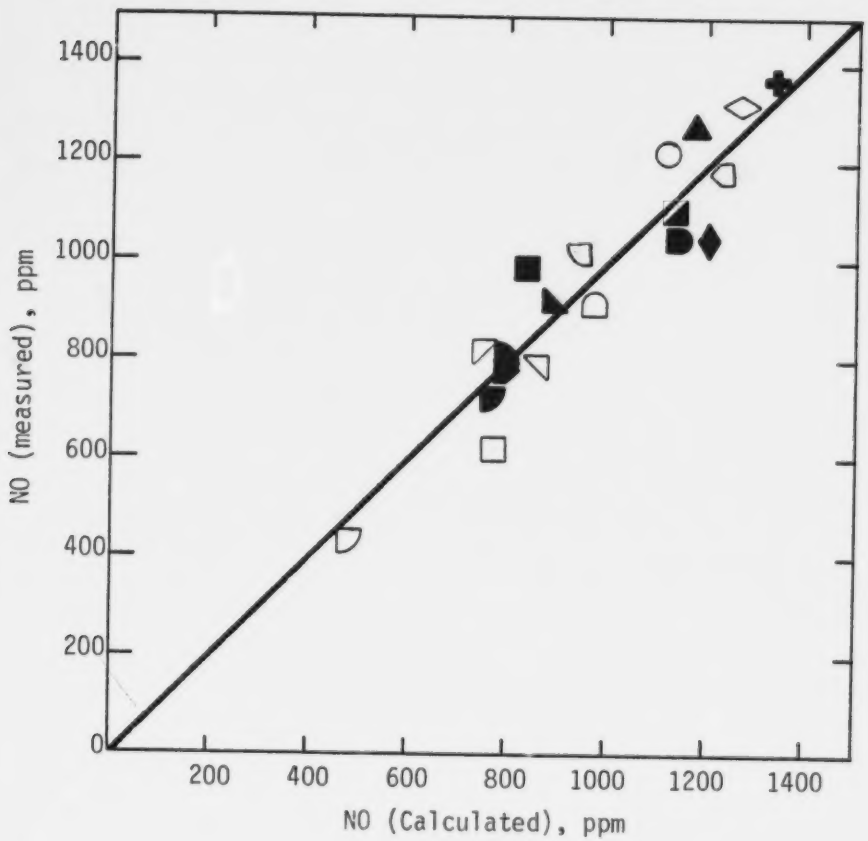

Figure 18. Emissions can be calculated by
NO = 318 + 702 (N) + 0.188 (HCN) - 0.347 (Char N), where
N = wt. % nitrogen in original coal (DAF),
HCN = inert pyrolysis HCN yield, PPM equivalent, and
Char N = modified ASTM char nitrogen, PPM equivalent.

5.0 STAGED COMBUSTION RESULTS

The previous section of this report discussed the fate of coal-bound nitrogen during coal combustion and the availability of oxygen was found to be one of the major factors controlling fuel NO formation. Consequently, modification of the combustion process to allow pulverized coal to react initially under oxygen deficient conditions (staged combustion) is the most effective method of controlling NO formation in pulverized coal fired combustors. Staged combustion can be accomplished by several different techniques. The combustion process can be staged either by physically separating the fuel rich zone from the burnout zone, or by using the burner to delay the mixing of the fuel with all of the combustion air.

This section of the report will describe the results obtained in bench scale studies to define the optimum conditions for staged combustion and to assess the influence of fuel properties on those conditions. In these studies, the combustion system was considered as a series of idealized reactors in which time/temperature history and stoichiometry could be controlled independently; no attempt was made to achieve this control with experimental hardware identical to that which would be used in a full scale unit.

Section 2.0 described the tunnel furnace configuration which was used in these experiments. The significant features included a radiation shield, which served to minimize the effects of downstream parameters on particle heat-up and ignition, and a refractory staging choke, which isolated the fuel rich and fuel lean stages. The second stage air was added through a divergent (45°) air injection ring downstream of the staging choke. Removable cooling coils could also be placed upstream or downstream of the staging choke to remove heat before or after the addition of the second stage air.

The discussion of the staged combustion studies has been conceptually divided into first and second stage effects. This section begins by considering the influence of the primary zone combustion parameters on the amount and speciation of reactive nitrogen (gaseous and solid) leaving the first, fuel rich zone and on the exhaust NO_x emissions. Next, the effect of fuel properties on both combustion zones is reviewed. This section concludes by examining the complex influence of thermal environment on the overall process optimization.

5.1 Primary Zone Combustion Parameters

Primary Zone Stoichiometry

Figure 19 summarizes the staged combustion results obtained with a premixed primary zone for fuels of different ranks. In these experiments, the staged combustion air was injected 1.2 meters from the burner and all of the data were obtained at 25 percent overall excess air (SR_t = 1.25). The results indicate that with the exception of the medium volatile bituminous coal (Coal H) as the first stage stoichiometry (SR_1) was progressively reduced, the exhaust NO_x emissions decreased, reached a minimum, and then increased. However, with Coal H (and with anthracite, coal char, and the medium volatile bituminous Coal V, not shown in Figure 19) exhaust emissions did not exhibit this minimum value. (Exhaust NO emissions as a function of SR_1 for all the non-U.S. coals tested are presented in Appendix B.) In addition, fuel type was found to influence both the stoichiometric ratio for minimum NO emissions and the NO/SR gradient.

Detailed in-flame measurements of gas species concentration and solid composition and concentration were made for 9 coals to define the relationship between first stage combustion parameters and the oxidizable nitrogen leaving the first stage. Figure 20 shows a set of typical results for the Coal A lignite. Similar results for all of the other coals are contained in Appendix C. All gas phase concentration measurements are shown on a dry, zero percent O_2 basis, neglecting the influence of H_2 in the rich gases. Samples were withdrawn from the furnace using a stainless steel water-spray probe. Gas phase, HCN and ammonia species were collected in a gas-washing unit which consisted of an impinger in series with a bubbler containing a fritted glass cylinder. The sample solutions were subsequently analyzed for CN^- and dissolved ammonia using specific ion electrodes. Isokinetic sampling was used to collect the solid samples, and the ultimate composition was determined with the Perkin Elmer 240B elemental analyzer.

Figure 20 indicates that as the first stage stoichiometry was reduced, the NO exiting the first stage decreased. However, this was compensated for by an increase in other oxidizable nitrogen species (both gas and solid phase). This behavior is analogous to that reported by Takagi et al (1979) for CH_4/NH_3 flames, by Altenkirch et al (1979) for flat coal flames, and by

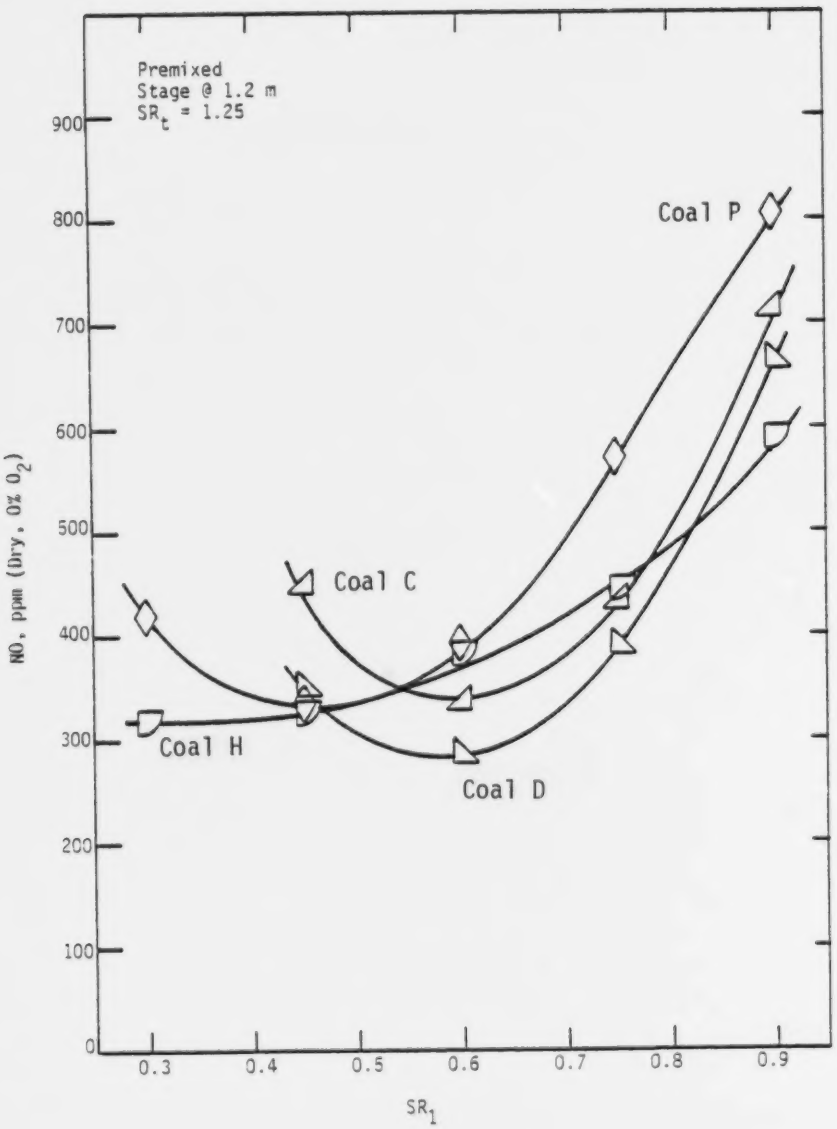

Figure 19. Influence of First Stage Stoichiometry on Exhaust NO Emissions.

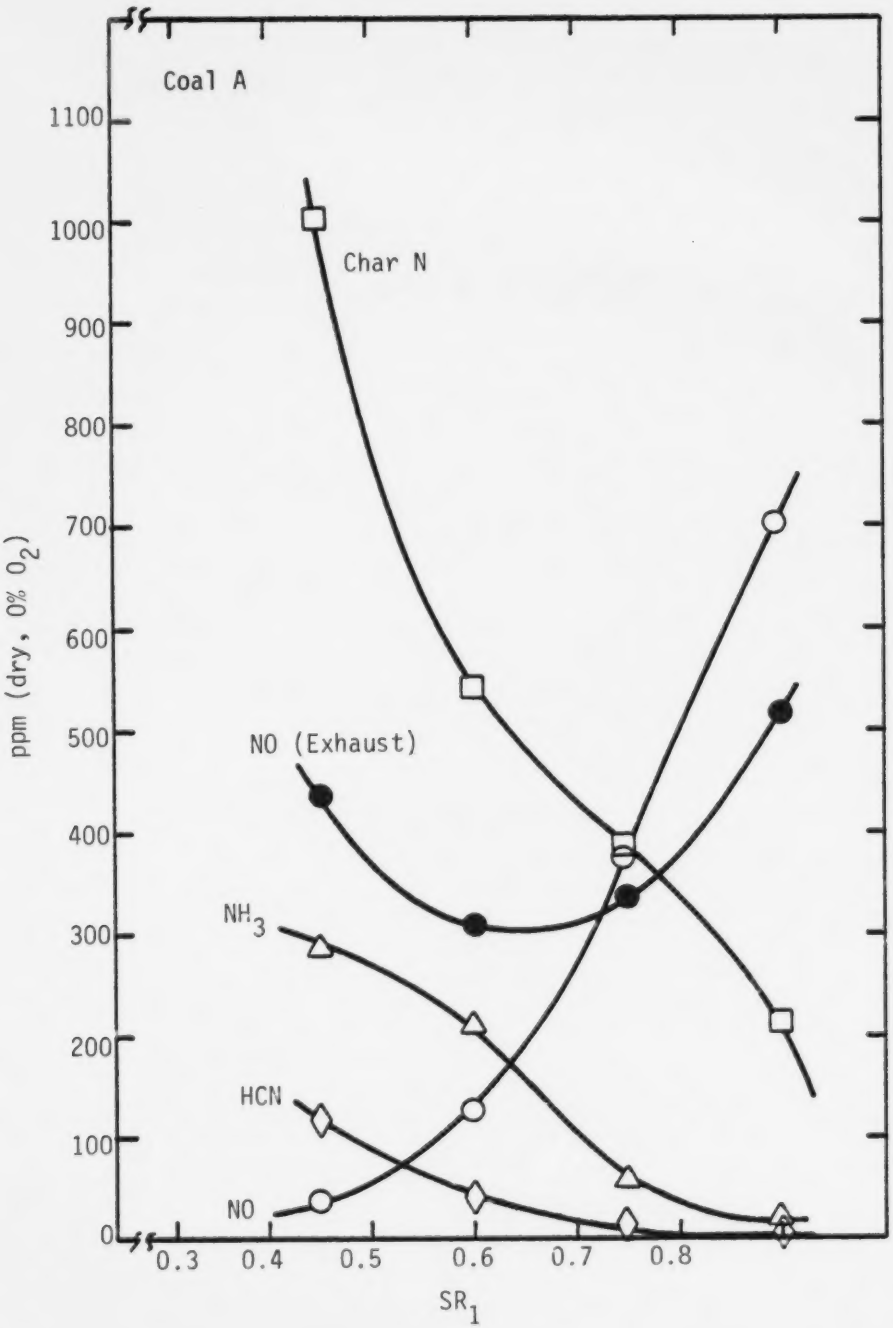

Figure 20. XN (NO, NH_3, HCN) and Char N Concentrations at the First-Stage Exit.

Chen et al (1981) for pre-mixed American coal flames. At stoichiometric ratios below 0.65 significant amounts of reduced nitrogen species (HCN and NH_3) and char containing solid-phase nitrogen compounds were carried into the second stage flame. In fact, below a first-stage stoichiometry of 0.6, the char nitrogen concentration significantly exceeded the gas-phase TFN (NO + HCN + NH_3). Thus, the reactants at the exit of the first stage contain oxidizable nitrogen in both the gas and solid phase.

At the temperatures in the bench-scale reactor, it is reasonable to assume that the final NO value is due primarily to the oxidation of the nitrogen species exiting the first stage. The minimum in exhaust NO concentration probably occurs because of the difference in conversion efficiency of the oxidizable nitrogen species (char nitrogen, NO, NH_3, and HCN) in the second-stage flame, and the fact that there is a minimum oxidizable nitrogen concentration. One approach to staged combustion would require that all of the coal-bound nitrogen be driven into the gas phase and that the combustor be operated to minimize the gas-phase nitrogen species at the end of first-stage. Alternatively, if the conversion of solid and gaseous nitrogen in the second-stage flames is markedly different, then some optimum reactant composition could exist in which the nitrogen is divided between the solid and gaseous phases.

Initial Fuel/Air Contacting

The excess air results presented in Section 4.0 indicated that the initial fuel/air mixing can strongly influence nitrogen oxide formation, and this is also true under staged combustion conditions. Figure 21 shows exhaust measurements for both pre-mixed and radial diffusion flames with the subbituminous coal, Coal D. In these experiments, the second-stage combustion air was added 1.2 meters from the burner and the overall stoichiometric ratio was held constant at 1.25. As discussed in Section 2.0, the radial diffusion burner produced a short, intense, bushy flame, while the pre-mixed burner produced a longer, one-dimensional flame. The exhaust data shown in Figure 21 indicated that at all stoichiometries tested, the radial diffusion burner produced less NO than the pre-mixed burner. Figure 22 shows the results of detailed in-flame measurements which were made at the end of the first stage (1.2 meters from the burner). The NO leaving the first stage of

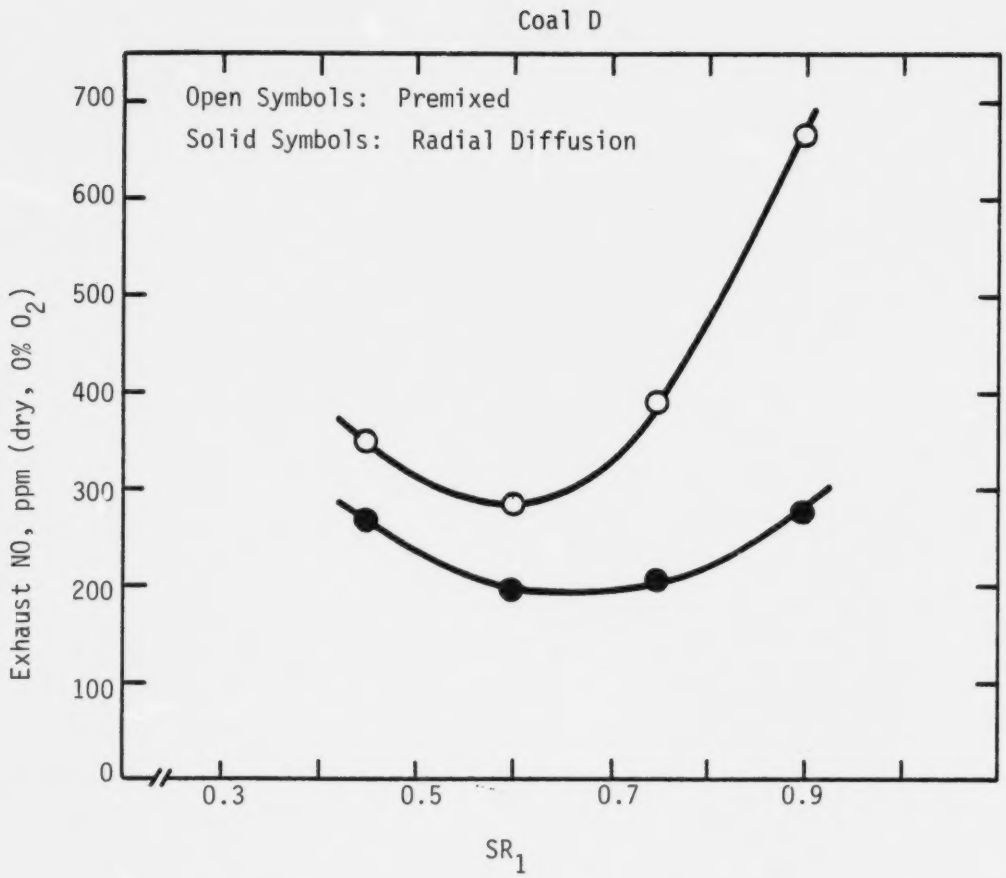

Figure 21. Influence of Initial Fuel/Air Contacting on NO Emissions Under Staged Combustion Conditions.

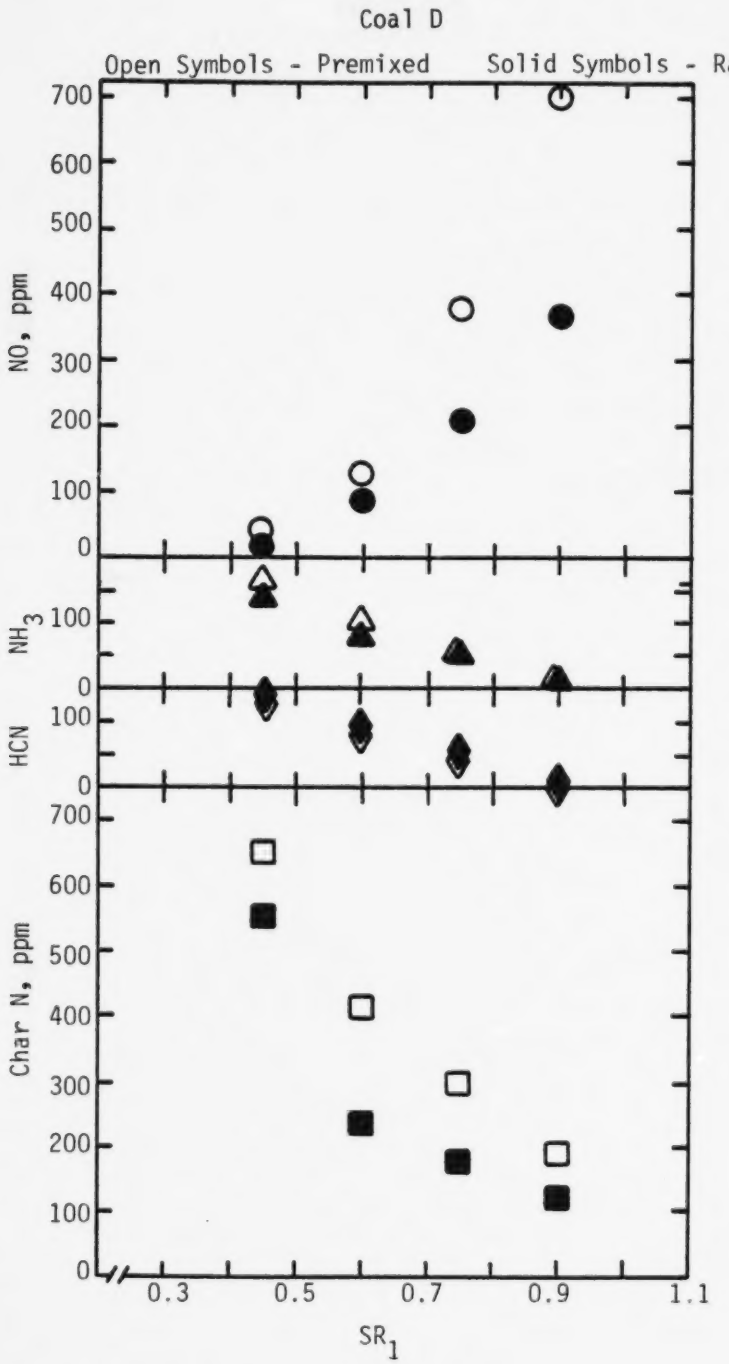

Figure 22. Influence of Initial Fuel/Air Contacting on XN Concentrations.

the reactor was decreased significantly when the radial diffusion burner was used. Visual observation of the flames suggest that this may be due to increased combustion intensity (higher local flame temperature) and to differences in local oxygen concentration. (In the pre-mixed case, the oxygen partial pressure is uniformly high until the fuel oxidation is nearly complete.) Burner type appeared to have relatively little influence on either HCN or NH_3. The char-nitrogen carry-through (into the second stage) was lower for all conditions tested with the radial diffusion burner. This, again, suggests that the radial diffusion burner produced higher local flame temperatures and, hence, larger rates.

Thus, it appears, based on the detailed in-flame measurements, that under relatively lean conditions (SR_1 greater than 0.7), the pre-mixed burner gives higher exhaust NO because it produces more NO early in the first stage. However, under very fuel-rich conditions, the pre-mixed burner gives higher NO in the exhaust, because of higher char-nitrogen carry-through. Similar results were obtained by Chen et al (1981) for a Utah bituminous coal. However, the effect was much smaller for a North Dakota lignite coal.

Particle Size

Figure 23 shows the influence of coal particle size on exhaust NO emissions for the sub-bituminous coal (Coal D). As noted previously, under excess air conditions (SR_1 greater than 1.0), small particles resulted in increased exhaust NO emissions. However, under staged combustion conditions, decreasing the mean particle size from 69 microns (normal) to approximately 39 microns (fine) significantly decreased the minimum emission level. This behavior is in direct agreement with that reported in Section 4.0 for axial diffusion flames and is believed to be because with the small particles more nitrogen can be driven out of the solid phase into the fuel-rich, first stage where N_2 formation is favored. This effect would be particularly significant in a staged combustion system with a small primary zone residence time.

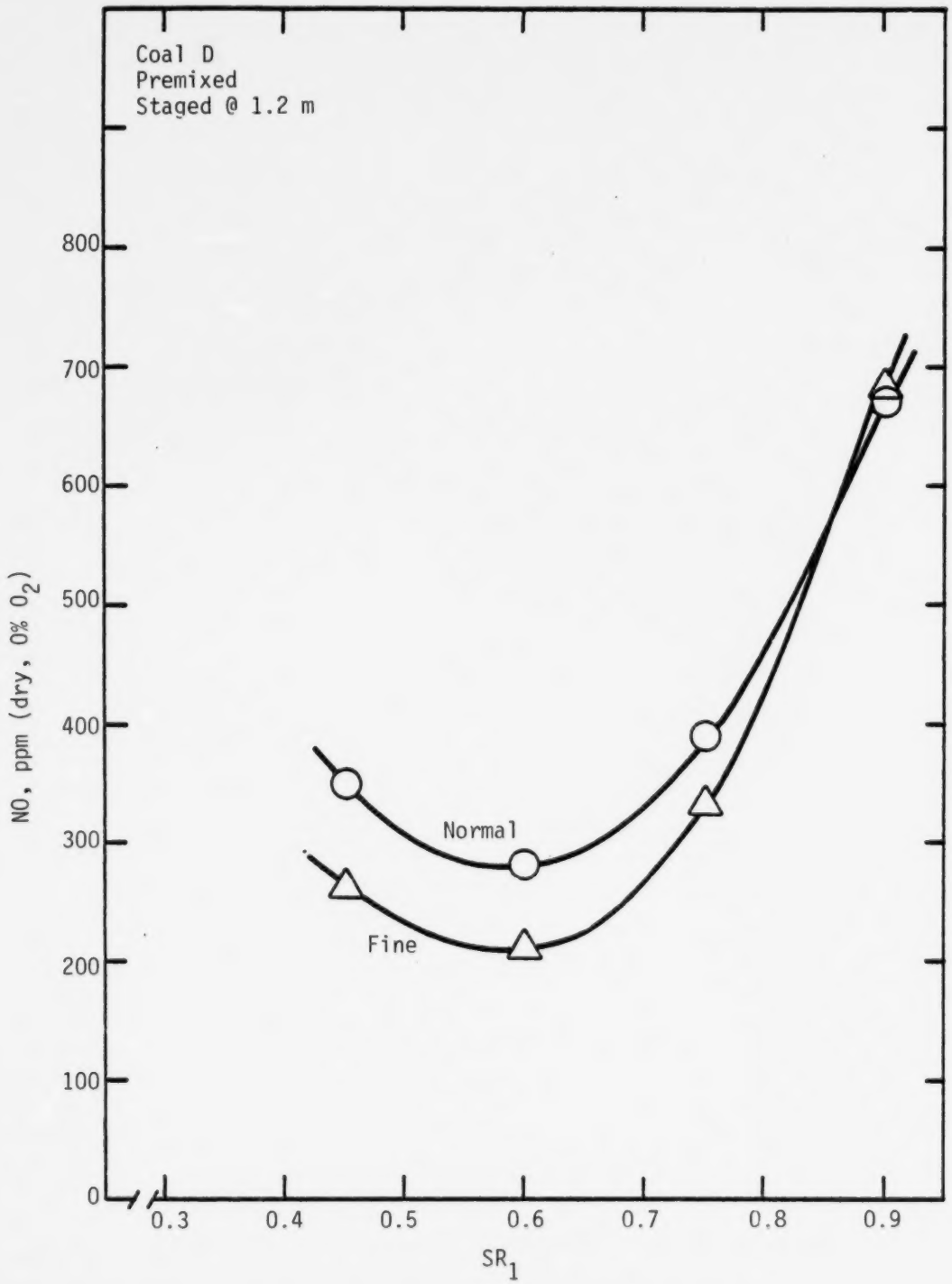

Figure 23. Influence of Particle Size on NO Emissions.

5.2 Fuel Properties

5.2.1 Overall Effects - Exhaust NO Emissions

Figure 24 shows the minimum NO emissions for all the IEA coals as a function of percent nitrogen in the fuel. In each case, the minimum value was obtained from an experiment in which the primary zone stoichiometry was varied from 0.45 through 0.9. Appendix B contains the detailed results for each of these tests. All of the data shown in Figure 24 were obtained with an overall stoichiometry of 1.25 and with the staging air injection at 1.2 meters from the burner. The results indicate that, in general, the minimum NO emissions increase slightly with increasing fuel nitrogen content. Coal I contained the largest amount of fuel nitrogen and produced the highest minimum emissions. Coal M gave the lowest minimum emissions, except for the predried Australian brown coal. Figure 24 also indicates that effects other than total fuel nitrogen content are of major importance. For example, both Coal N and Coal P are high volatile, bituminous fuels with approximately 1.8 percent nitrogen (DAF), yet Coal N produced significantly lower minimum NO emissions. This difference is apparently related to the speed with which the volatile components are evolved and the relative importance of char nitrogen, as will be discussed in the following sections.

Figure 25 shows the same minimum NO exhaust emissions data presented in terms of percentage conversion. (Because of the thermal conditions within the reactor, it was assumed that thermal NO_x formation in the second stage was small.) The data shown in Figure 25 indicate that percent conversion decreases with increasing fuel nitrogen content. These results are consistent with the early work of Martin et al (1971) and confirm that the reactions forming N_2 are bimolecular while the oxidation reactions involve only a single XN species.

5.2.2 First-Stage Processes

Detailed in-flame measurements of gas species concentrations and solids composition and concentration were made for 9 coals to define the relationship between the reactive nitrogen species leaving the first stage, the exhaust NO_x emissions, and the original coal composition. Ultimately, fuel properties influence:

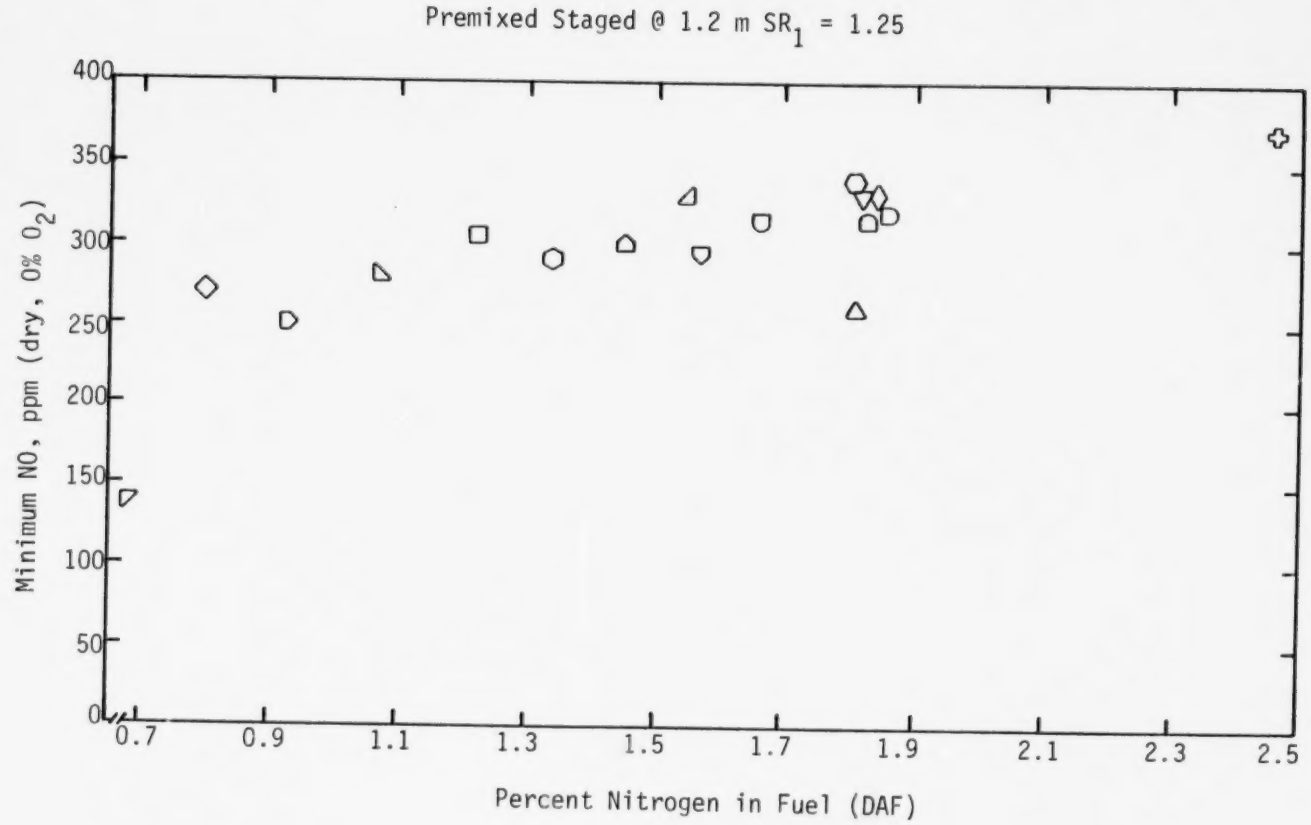

Figure 24. Minimum NO Emissions as a Function of Fuel Nitrogen Content.

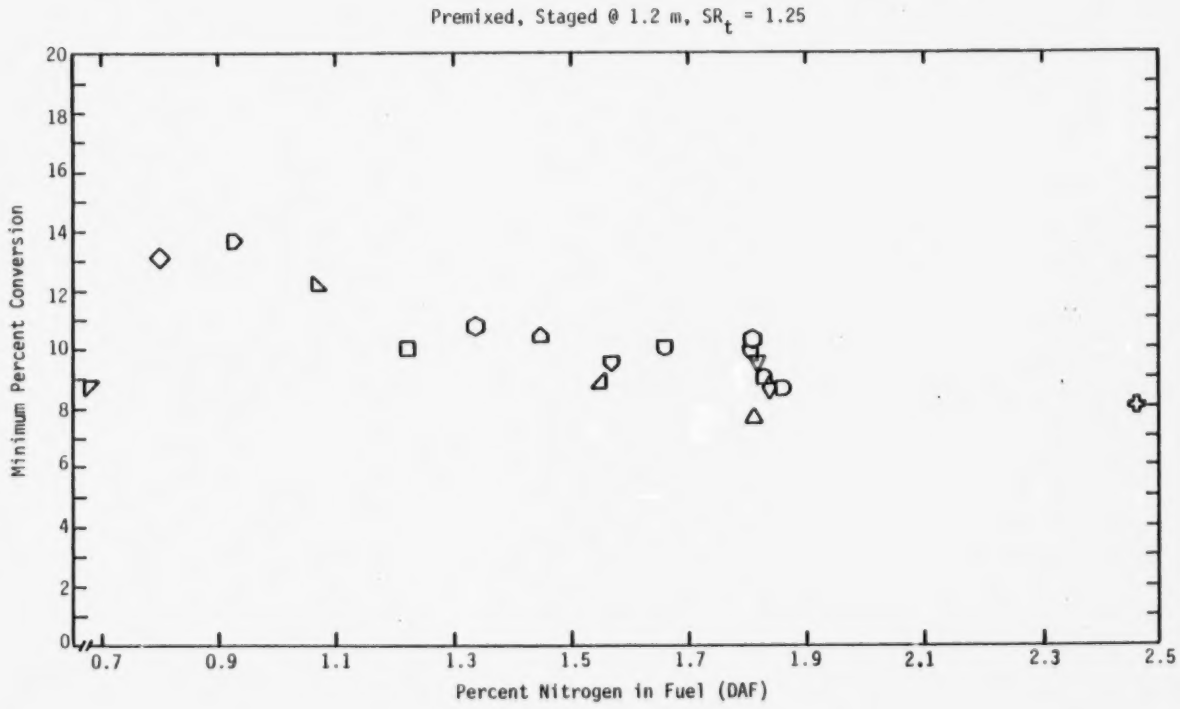

Figure 25. Minimum Conversion of Fuel Nitrogen to NO Under Staged Combustion Conditions.

- The total amount of reactive gas-phase nitrogen (TFN).
- The partition of the TFN between the various XN species (e.g., HCN, NH_3, NO, etc.).
- The amount of nitrogen remaining in a solid char.

Fuel properties also influence second-stage processes indirectly, because they control the reactants entering the second stage.

Total Gas-Phase Nitrogen

Figure 26 summarizes the total gas-phase, fixed nitrogen (TFN = NO + NH_3 + HCN) concentrations for 9 IEA coals and the pre-dried Australian brown coal. These data were all obtained at a distance of 1.2 meters from the burner and with a premixed primary zone stoichiometry of 0.6. In general, the TFN increased with increasing fuel nitrogen content in the parent coal; however, within any rank and nitrogen content, TFN concentrations varied somewhat. The most dramatic exception to the general case was the high volatile bituminous Coal N which had extremely low TFN concentration at the end of the first stage (1.2 meters). As expected (based on the exhaust NO emissions) Coal I produced the largest amount of TFN at the end of the first stage, and the pre-dried Australian brown coal produced the least TFN.

TFN Partition

Figure 27 summarizes the influences of coal composition on distribution of total fixed nitrogen species in the gas phase. The solid symbols are the IEA coals, and the open symbols are from the previous work of Chen et al (1981). Figure 27 presents the TFN partition results as a percentage of the original coal nitrogen for a constant first-stage stoichiometry (SR_1 = 0.6). All of the measurements were made at the exit of the first stage (1.2 meters). Figure 27a shows the NH_3 results as a function of coal rank. The fraction of the original coal nitrogen converted to NH_3 in the first stage increased significantly with decreasing coal rank. The first-stage NO concentrations exhibited essentially the reverse trend; increasing the coal rank decreased the fraction of the original nitrogen which exited the first stage as NO. The only major exception to this generalization was the high volatile, bituminous Coal M which produced exceptionally large amounts of NO at the first stage exit. This may have been because Coal M proved to be difficult to burn

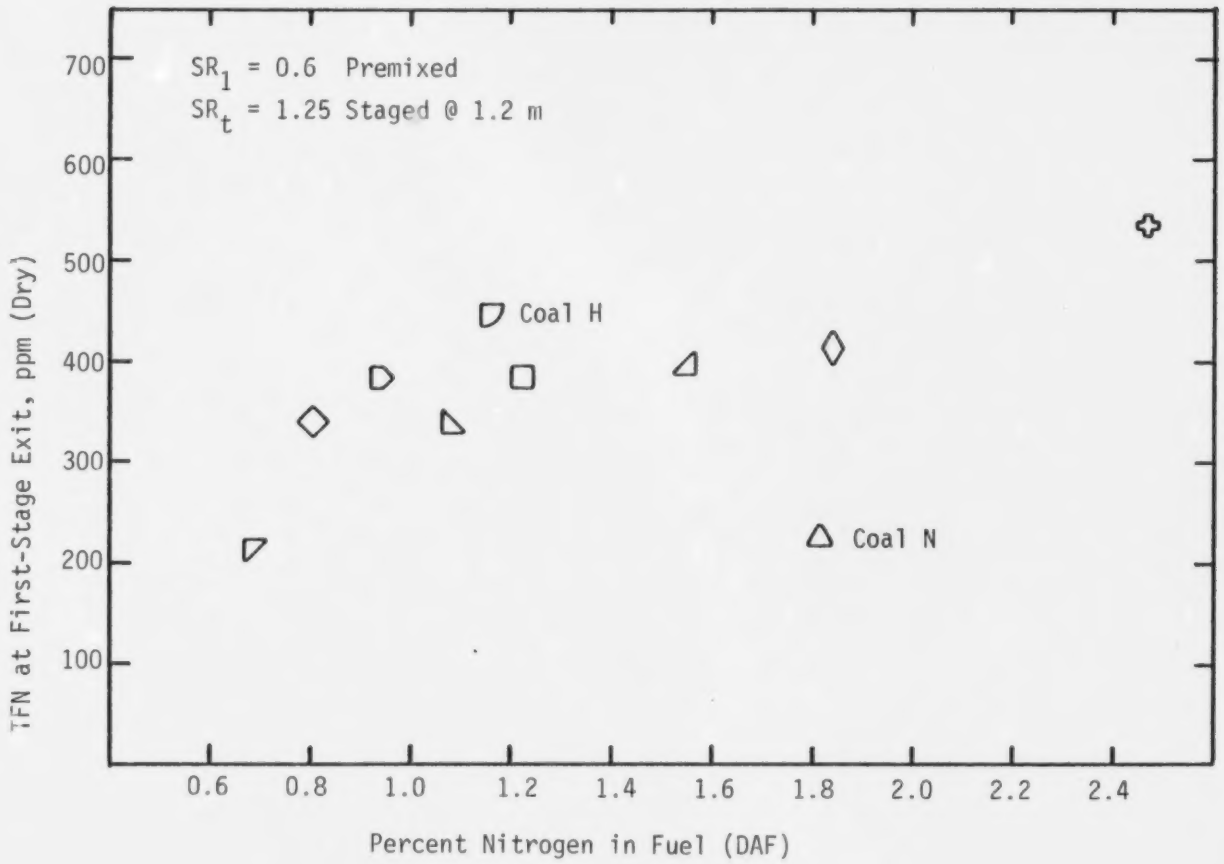

Figure 26. TFN Content at the Exit of the First Stage as a Function of Fuel Nitrogen Content.

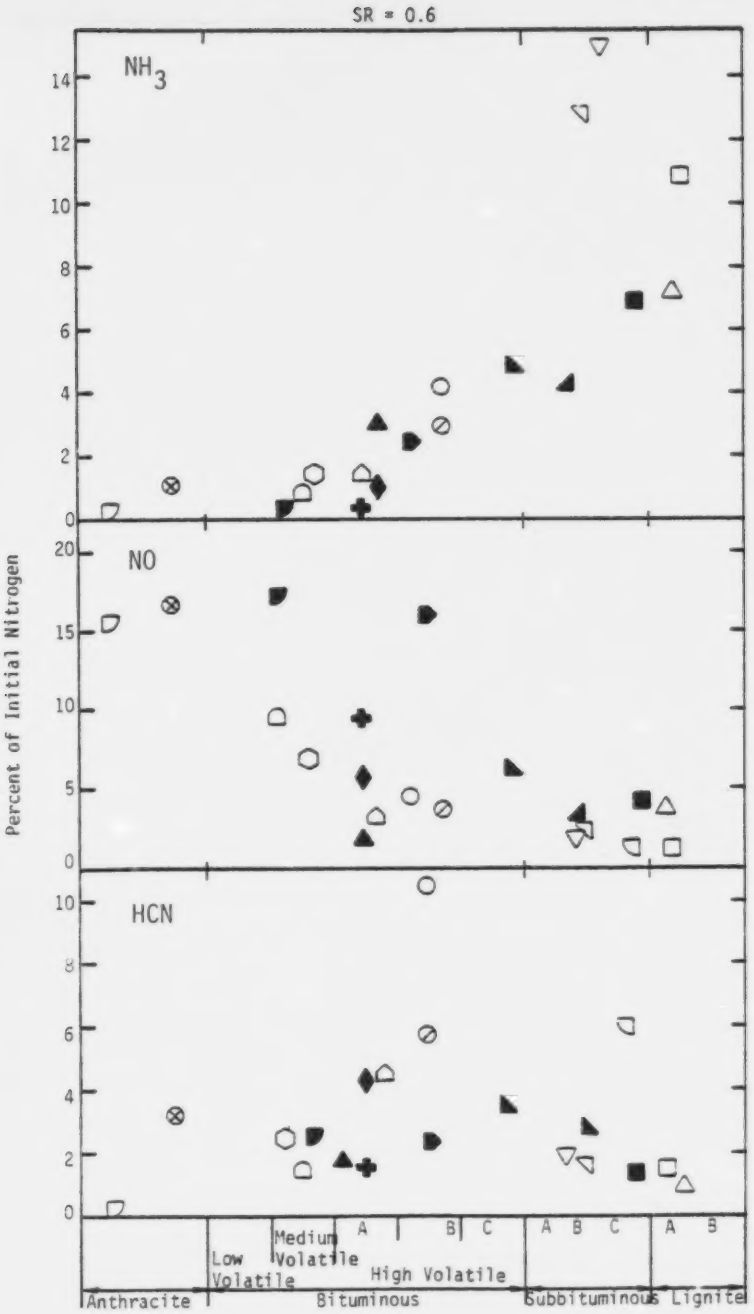

Figure 27. TFN Partition as a Function of Coal Rank.

and, therefore, the oxygen concentrations in the first portion of the primary zone were unusually high. Figure 27c shows the HCN results and indicates that, in general, HCN concentrations were small (note the different ordinate axis). Only the Utah bituminous coal (○) produced a significant amount of HCN at a first-stage stoichiometry of 0.6.

Figures 28, 29 and 30 present typcial results for the HCN, NH_3, and NO concentrations at the end of the first stage as a function of first-stage stoichiometric ratio. The data are plotted on a cumulative basis and have been corrected to 0 percent oxygen dry, neglecting the influence of hydrogen on the total flue gas volume. Figure 28 shows the results for the medium, volatile, bituminous Coal H and the high volatile, A bituminous Coals P and N. Coal H, as with all low volatile coals tested to date, produced relatively little HCN and NH_3; NO was the dominant TFN intermediate at all conditions tested. This difference is believed to be due in part to the influence of gas-phase reactions. With the low volatile fuels, the initial oxygen is consumed more slowly because of the absence of large amounts of hydrocarbon volatiles. This promotes the formation of NO from the coal nitrogen species (either volatile or solid) under the oxidizing conditions. In addition, when there are significant hydrocarbons present, early NO may be converted to HCN and/or NH_3. However, with a low volatile fuel, such as Coal H, once NO has been produced there are relatively few paths available to convert it to either NH_3 or HCN. For the high volatile bituminous (Coals P and N), the importance of HCN increases as the first-stage stoichiometry is decreased. Figure 29 shows similar results for two high-volatile B bituminous coals (Coals I and M). The Coal M data is slightly unusual in that there is no minimum in the total fixed nitrogen; this appears to be because, at low stoichiometric ratios, the char nitrogen retention increases dramatically as will be discussed later. The data shown in Figures 28 and 29 indicate that the HCN concentration usually equals, or exceeds, NH_3 concentration for the bituminous coals at all stoichiometries, and this is in agreement with the earlier work on American bituminous coals.

Figure 30 shows similar results for the sub-bituminous and lignite coals. All of the lower rank coals tested produced large amounts of NH_3 at stoichiometric ratios below 0.65. HCN concentrations were significantly less than NH_3 levels at all stoichiometries for all sub-bituminous and

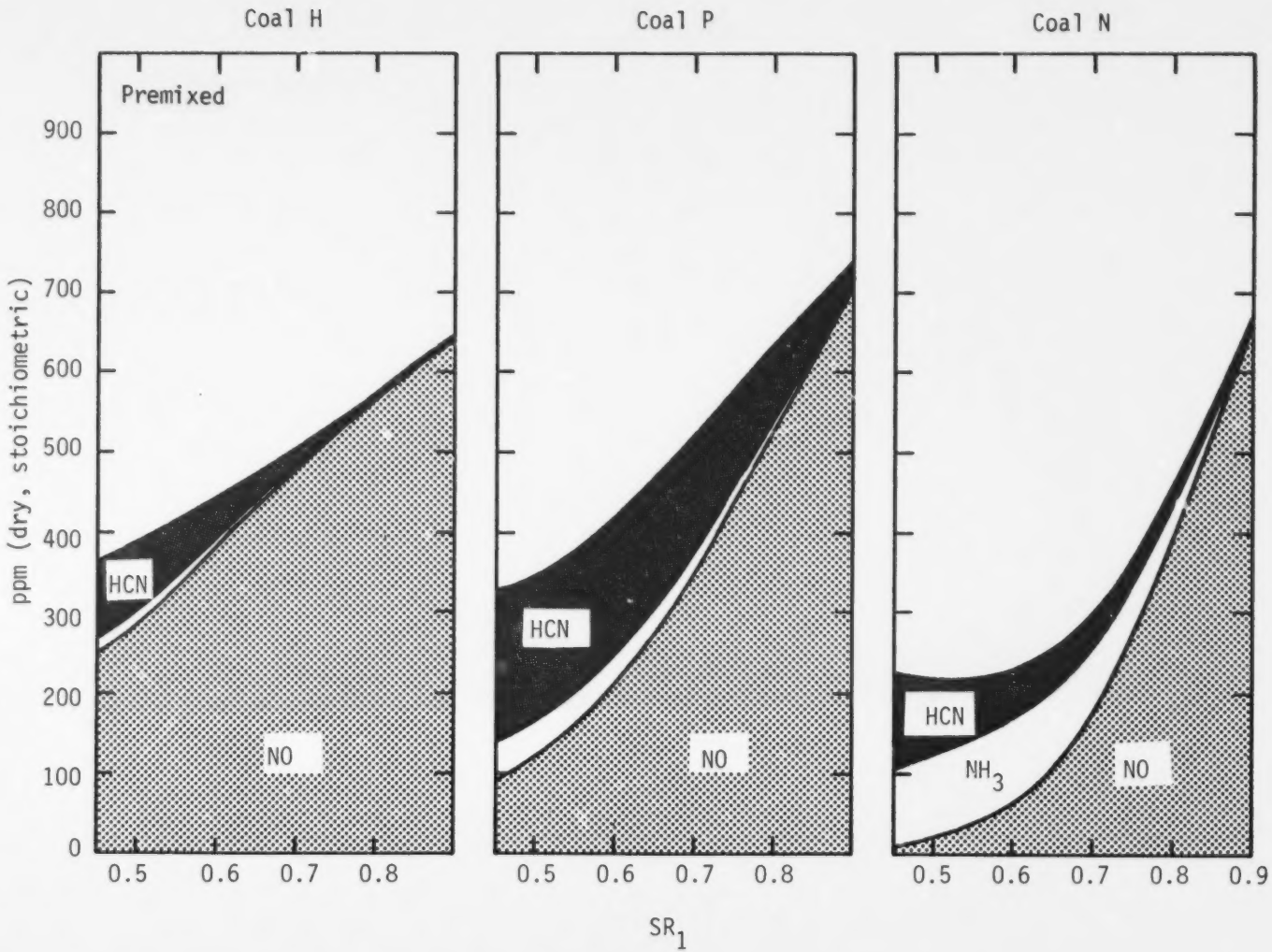

Figure 28. Distribution of TFN Species.

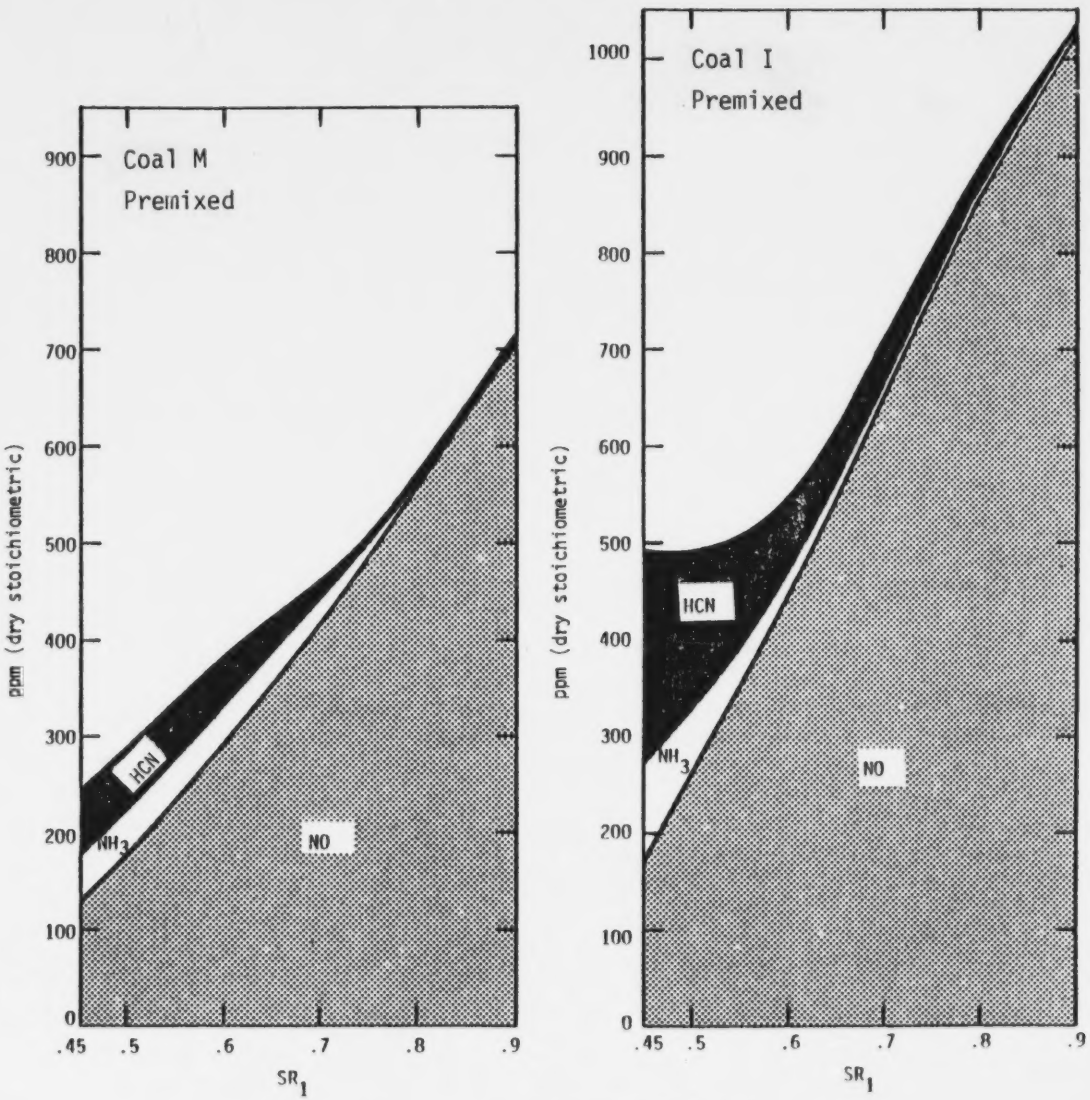

Figure 29. TFN Distribution.

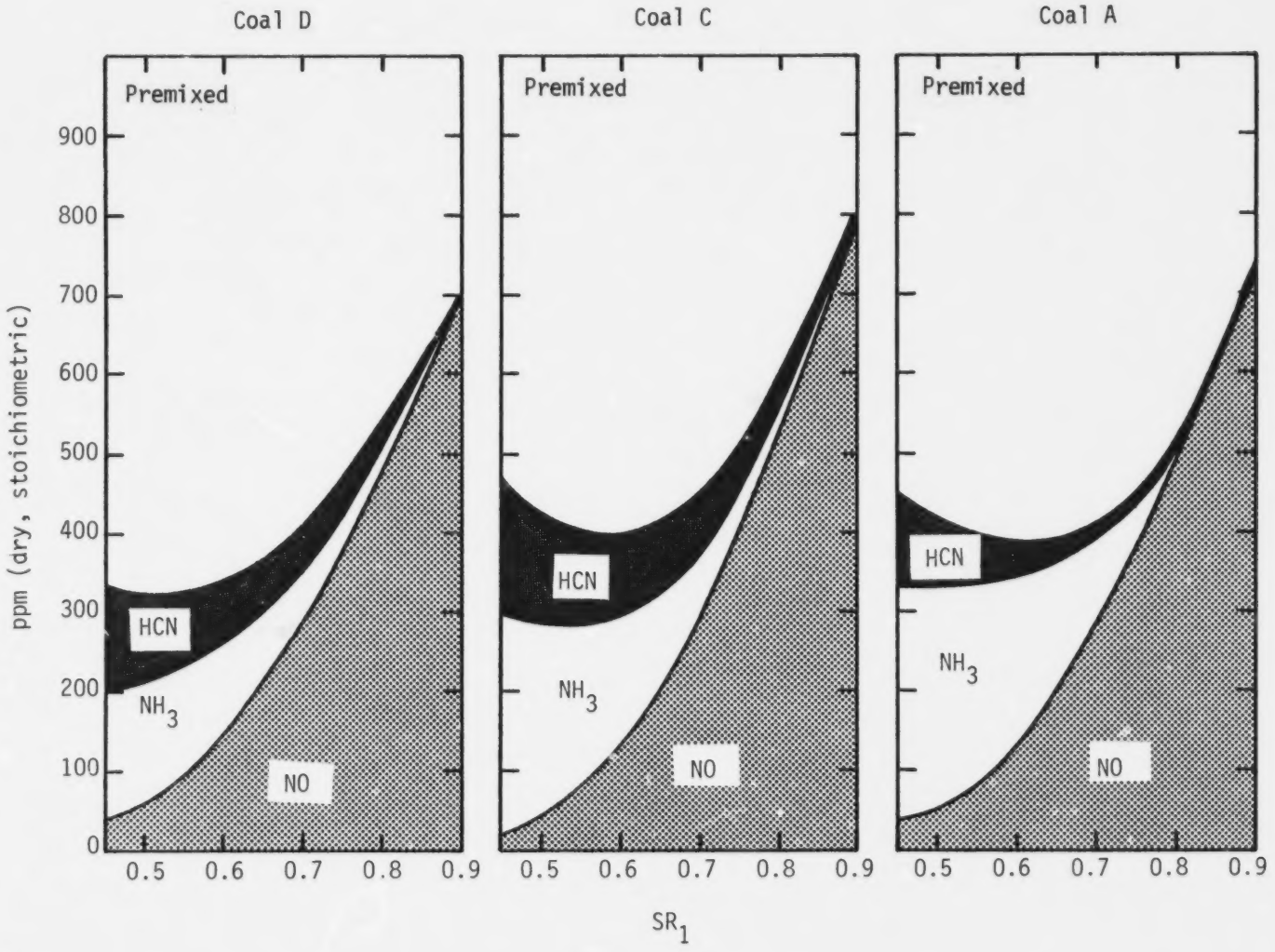

Figure 30. TFN Distribution.

lignite coals tested, and NO concentrations at the first-stage exit were also low relative to the bituminous coals.

These data suggest that the TFN chemistry is coupled to the hydrocarbon volatile chemistry. Bituminous coals tend to produce large amounts of alephatic hydrocarbon volatiles and this undoubtedly results in HCN being the dominant TFN species at low stoichiometric ratios. In contrast, sub-bituminous and lignite coals tend to produce large amounts of CO, CO_2, and H_2O. In this case, NH_3 appears to be the favored species.

Solid Phase Nitrogen Retention

The fraction of the initial nitrogen, which was retained in the char at the exit of the fuel-rich first stage, is shown in Figure 31 as a function of the "nitrogen retained in the ASTM char." The latter was determined by analyzing the nitrogen content of the solid which remained at the conclusion of the standard ASTM approximate analysis procedure. These data indicate that, in general, those coals which tend to retain their nitrogen in the ASTM proximate procedure (1100°C) also tend to retain their nitrogen in a solid phase during actual combustion. The sub-bituminous Coal C exhibited the least tendency toward solid-phase nitrogen retention in both experiments, and the medium volatile bituminous Coal H exhibited the greatest tendency to retain nitrogen in the solid phase in both tests. These data suggest that Coal H would be a particularly difficult fuel to control NO_x emissions with a low NO_x burner, because it would tend to retain its nitrogen beyond the small fuel-rich burner core.

5.2.3 Second-Stage Processes

The second stage of the bench-scale reactor system can be considered as an excess air flame burning partial oxidation products produced in the first stage. The ultimate yield of NO will be dependent upon the first-stage reactants (fuel composition, gas-phase nitrogen content, and char nitrogen content) as well as fuel/air contacting parameters such as the rate at which the second-stage air is added. The previous section defined the influence of the fuel properties on the amount and chemical speciation of the gas and solid phase nitrogen components leaving the first stage. This section contains a detailed examination of the fate of those nitrogen species in the

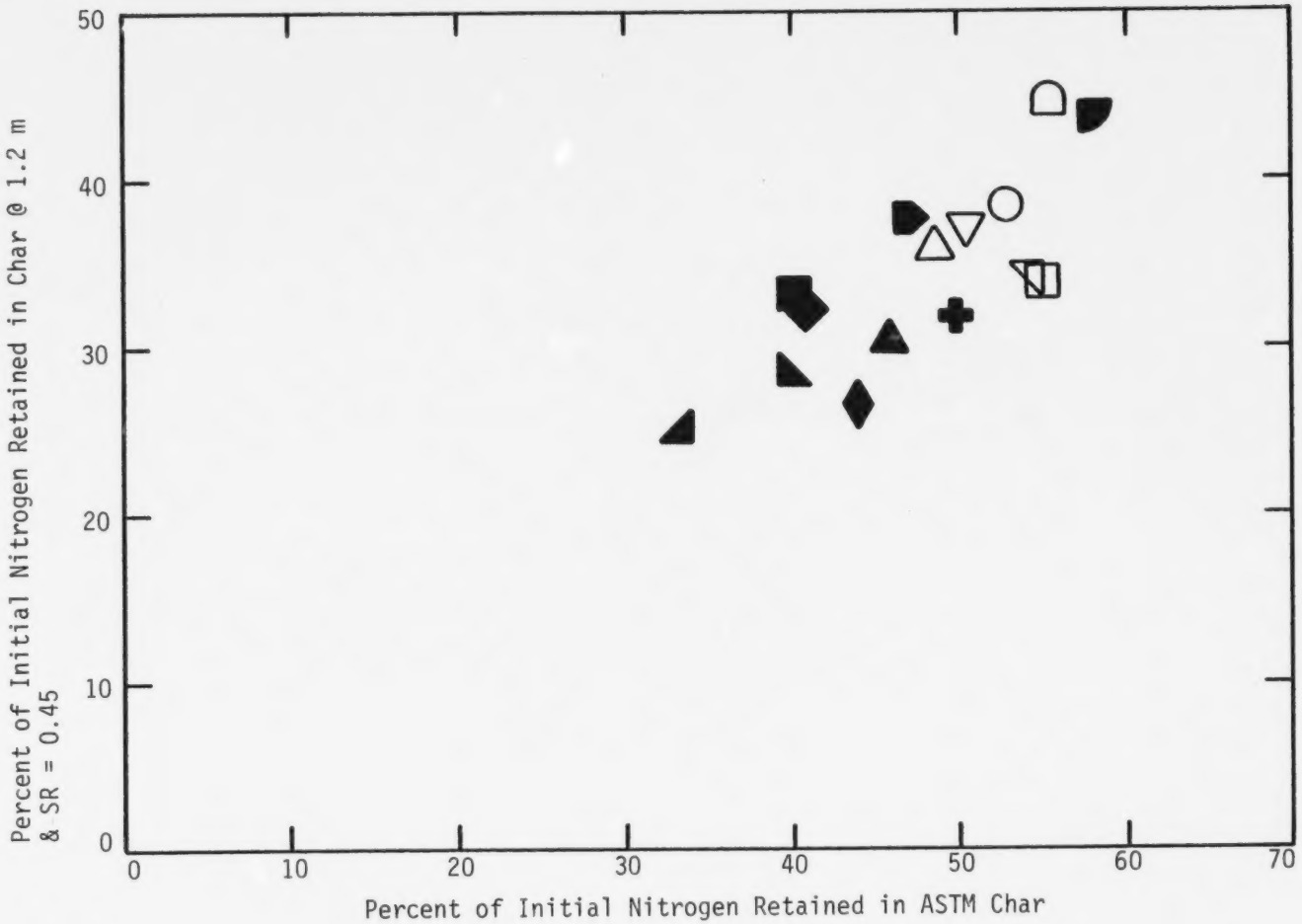

Figure 31. Correlation of Char Nitrogen with Modified ASTM Analysis.

second-stage flame. Minimization of exhaust NO emissions through staged combustion technology requires an overall optimization of both stages.

TFN Conversion

Figure 32 is a composite plot obtained from the results of Chen et al (1981) which indicates the conversion of gaseous fuel nitrogen species to NO in the second-stage flame. Initially, tests were conducted with C_3H_8/NH_3 and C_3H_8/NO flames in the first stage (no solid phase present). The percent TFN conversion in the second stage was computed based upon detailed species measurements (NO, HCN, and NH_3) at the exit of the first stage and on the exhaust NO. These results indicated that under relatively mild staging conditions where NO was the dominant TFN species (generally SR_1 greater than 0.75), the second-stage conversion of TFN to NO is very high (approximately 90 percent) and relatively insensitive to total TFN level over the range of interest. Under these conditions, only a small amount of the combustion is actually occurring in the second stage, and the second stage "fuel" is primarily CO. However, as the first-stage stoichiometry was further reduced, and the dominant TFN species became NH_3 + HCN, second-stage conversion decreased dramatically and became inversely dependent on the TFN level. (This behavior is somewhat analogous to that shown in Figure 25 for the IEA coals.) As noted previously, the transition from NO to HCN + NH_3 dominance corresponds to the onset of hydrocarbon formation. Thus, it is likely that the decrease in second-stage TFN conversion was a direct result of the second-stage "fuel" changing from CO to hydrocarbons and char. This behavior is essentially analogous to that observed by England et al (1981) with liquid fuels.

Figure 32 also shows data on second-stage TFN conversion in char/C_3H_8 flames, with and without ammonia. (By measuring TFN and exhaust NO in both flames it was possible to infer a mean TFN concentration.) These results show trends similar to those observed with gas flames and suggest that the solid phase has relatively little effect on the conversion of gaseous TFN in the second stage.

Thus, in summary, it appears that when the dominant TFN species entering the second stage is NO, the majority of NO will pass through the second-stage flame unreacted and will appear in the exhaust. When the dominant TFN

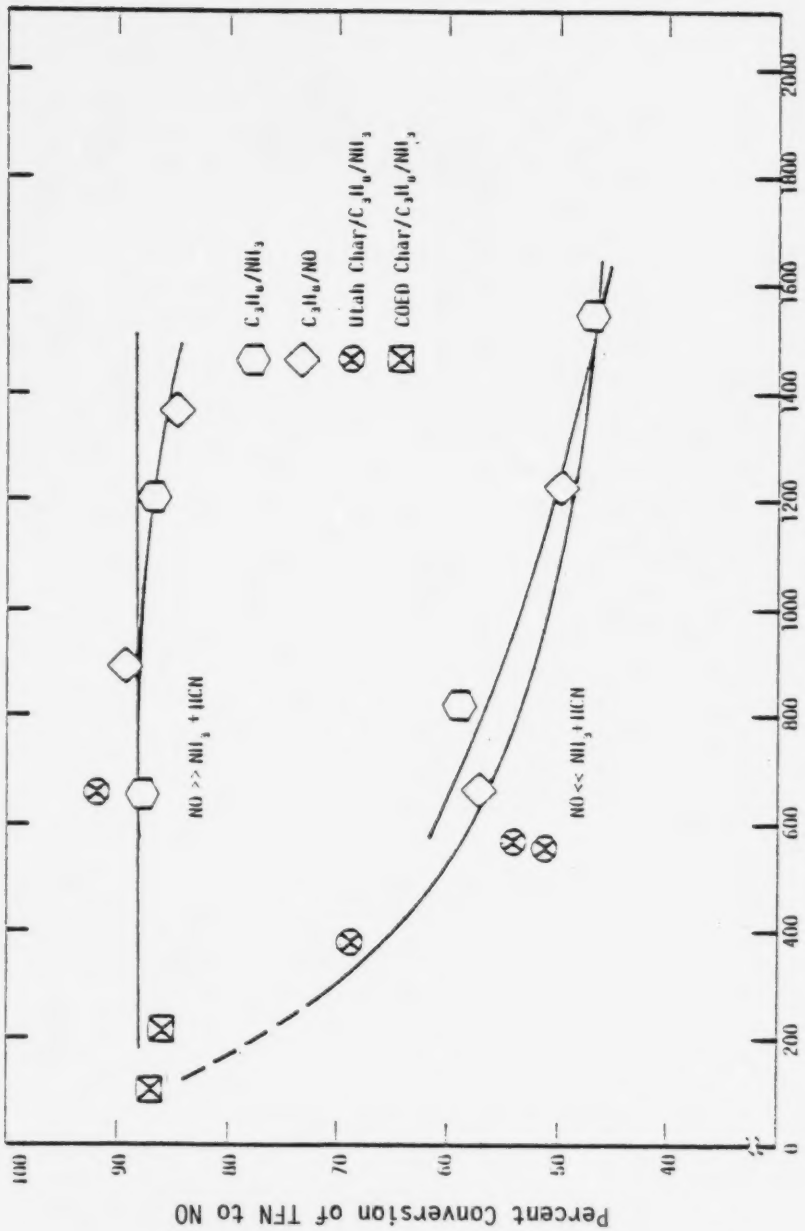

Figure 32. Second Stage Conversion of TFN Species.

species are HCN and ammonia, the conversion to NO will be reduced and inversely proportional to the amount of TFN present.

Solid Phase Nitrogen Conversion

To define the conversion of the solid-phase nitrogen in the second stage, Chen et al (1981) conducted a series of experiments with a COED char/C_3H_8 burning in an argon/oxygen atmosphere. This system eliminated thermal NO effects and provided a hot gas stream which entered the second-stage without large amounts of TFN species. Figure 33 summarizes these results and shows the calculated conversion data based on exhaust NO emissions. These results suggest that the conversion of char nitrogen in the second stage is 20 percent or less, and the conversion appears to increase slightly with decreasing first-stage stoichiometry.

Conversion Correlation

The previous sections have shown that the exhaust NO emissions depend on first-stage stoichiometry, on the amount and speciation of the TFN entering the second stage and on the amount of char nitrogen. Thus, the exhaust NO data were correlated with a model of the form:

$$NO\ exhaust = X_1\ (NO) + X_2\ (NH_3 + HCN) + X_3\ (C_N) + NO_{Th}$$

where

X_1 = conversion of NO

X_2 = conversion of NH_3 and HCN

X_3 = conversion of char nitrogen

NO_{Th} = thermal NO formation

in the second-stage flame. The TFN concentrations were correlated in ppm, dry 0 percent O_2 based on the detailed measurements at the end of the first stage. The char nitrogen (C_N) was used as equivalent ppm based on stoichiometric conversion of the remaining nitrogen.

As noted previously, NO conversion in the second stage flame is not a strong function of NO concentration (Figure 32). However, it does depend on first-stage stoichiometry (probably specifically on the hydrocarbon content of the second-stage flame). Data from pairs of Utah char/C_3H_8/NH_3 experiments

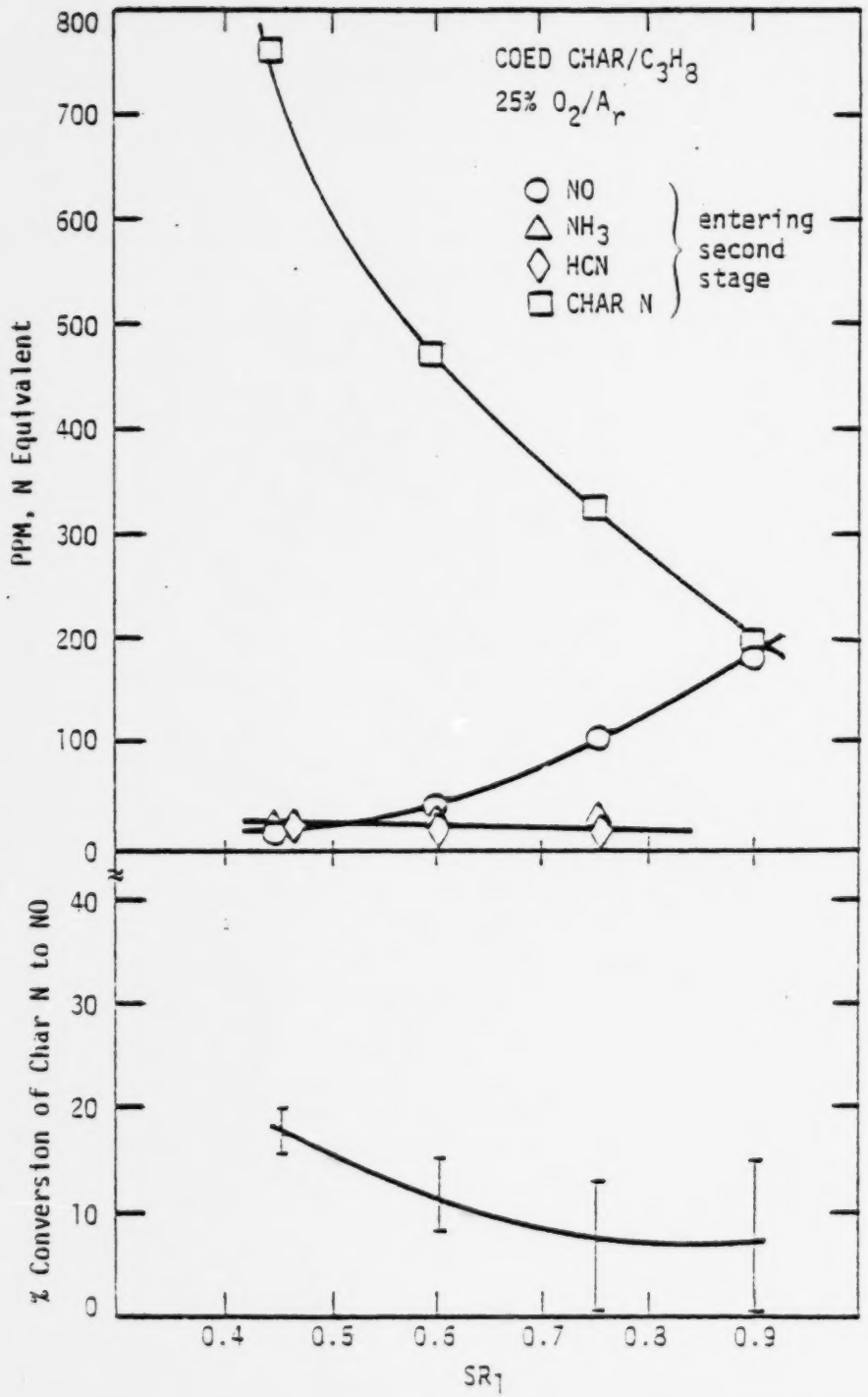

Figure 33. Solid Phase Nitrogen Conversion in the Second Stage.

indicated that as the SR_1 was reduced from 0.9 to 0.6, NO conversion dropped from approximately 89 percent conversion to 51 percent with no change in HCN or NH_3 concentrations. Therefore, NO conversion was modelled as:

$$X_1 = \alpha \, SR$$

where

α = correlation constant

Figure 32 also indicates that the conversion of HCN and NH_3 decreases with increasing TFN content; hence, a reciprocal model was used for these conversions:

$$X_2 = \frac{1}{\beta + \gamma \, (NH_3 + HCN)}$$

Chen et al (1981) found that char nitrogen conversion increased slightly with decreasing first-stage stoichiometry; therefore, it was modelled with a 1/2 order dependence:

$$X_3 = \delta \, (1\text{-}SR)^{1/2}$$

A multivariable linear regression program was used to calculate the required parameters based on the U.S. coal results. The resulting correlation was:

$$NO_{EX} = 0.87 \, SR \, (NO) + \frac{0.67}{1 + .004 \, (HCN + NH_3)} \, (HCN + NH_3) + 0.27 \, (1\text{-}SR)^{1/2} (CHAR \, N)$$

and the overall correlation coefficient (r^2) was 0.90 based in 26 data sets. A constant thermal NO term was included initially, but the regression analysis predicted that it was insignificant. Figure 34 shows the results of applying this correlation to the IEA data and indicates that the agreement is reasonable considering the wide range of coals (lignite-bituminous) and conditions (SR_1 = 0.45 - 0.90) which were included.

The equation suggests that first-stage NO has a very significant impact on the ultimate exhaust NO concentration; even at SR = 0.45, the retention of NO is predicted to be 39 percent. NH_3 and HCN conversion are predicted to decrease from 67 percent at low concentrations to 22 percent at 500 ppm of HCN + NH_3. Char nitrogen conversion was estimated to be approximately 20 percent or less.

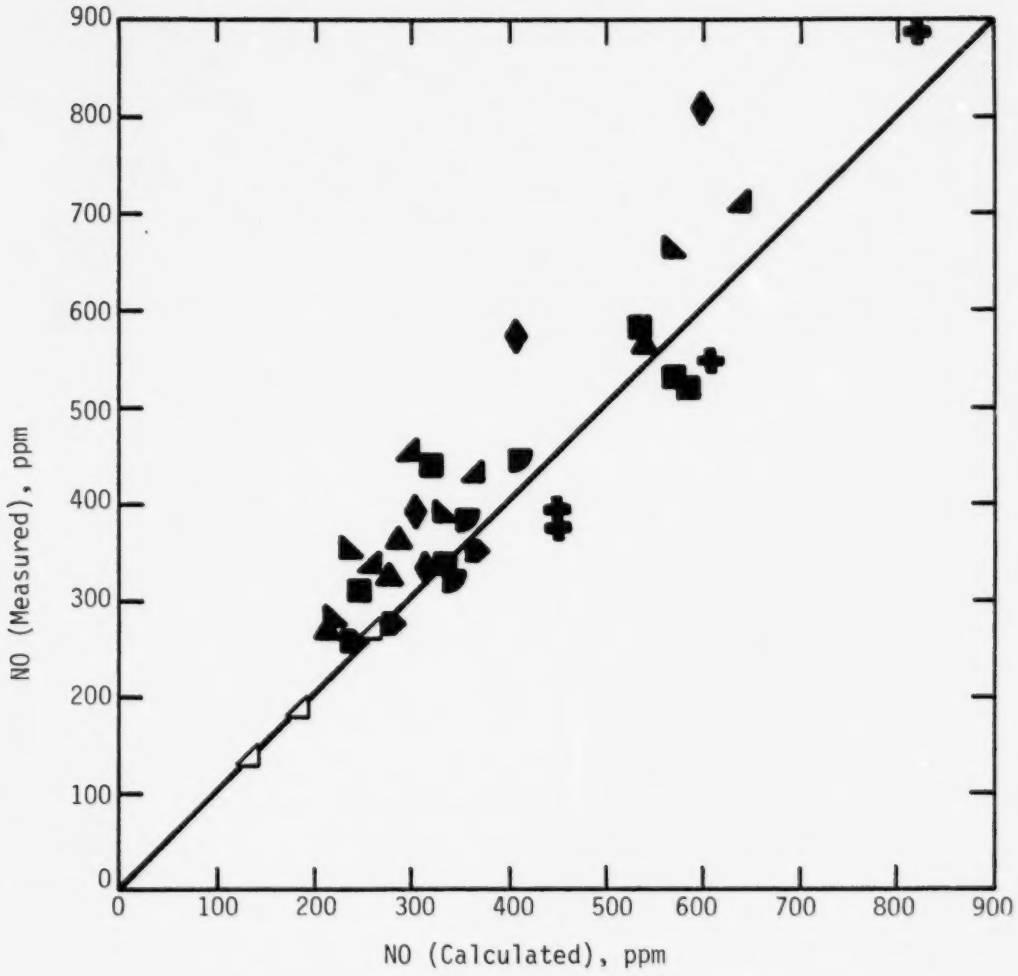

Figure 34. Exhaust NO can be calculated by

$$NO_{EX} = 0.87\ SR\ (NO) + \frac{0.67}{1 + 0.004\ (NH_3 + HCN)}\ (NH_3 + HCN) + 0.27\sqrt{1\text{-}SR}\ (Char\ N)$$

Relative Contributions

To evaluate the relative importance of the first-stage NO, the NH_3 + HCN, and the char nitrogen, in the formation of exhaust NO_x emissions, the correlation was used in the predictive mode. The TFN and solid nitrogen concentrations measured at the exit of the first stage with the sub-bituminous Coal C and the medium volatile bituminous Coah H were used with the correlation to predict the relative contributions to the exhaust NO emissions. Figure 35 shows the results of these predictions and indicates that even though the conversion of char nitrogen is relatively low, char nitrogen can be extremely important, particularly under very fuel-rich conditions. As expected, the model predicts that char nitrogen conversion in the second-stage flame is particularly important with the medium volatile Coal H.

These results suggest that optimum staged combustion technology must minimize first-stage NO formation and attempt to maximize the TFN decay in the first stage. Char NO formation in the second stage can also be very significant if large amounts of nitrogen are allowed to remain in the solid phase. Finally, the results suggest that low NO_x burner concepts will be much more effective with a fuel like Coal C which does not tend to retain its nitrogen in the solid phase than with the medium volatile Coal H.

5.3 Thermal Environment

The temperature profile in a staged combustion system can have a strong influence on the effectiveness of this controlled technique. In liquid fuel-fired systems, it is desirable to have a nearly adiabatic first-stage (England et al 1981); however, with pulverized coal, significant heat removal is beneficial (Johnson et al 1981; Chen et al 1981). To investigate this effect, a series of experiments was conducted with the IEA coals in which the first-stage of the reactor system was significantly cooled by inserting water-cooling coils along the walls. (See Section 2.0 for the details of this configuration.) Figure 36 shows the impact of this cooling on the bulk gas temperature at the end of the first stage for the sub-bituminous Coal D. At a first-stage stoichiometry of 0.6, the gas temperature was reduced approximately 200°K. Figure 37 shows the corresponding NO emissions measured in the exhaust for this test sequence, and indicates that increasing the rate of heat extraction in the first stage significantly decreased the exhaust NO_x at

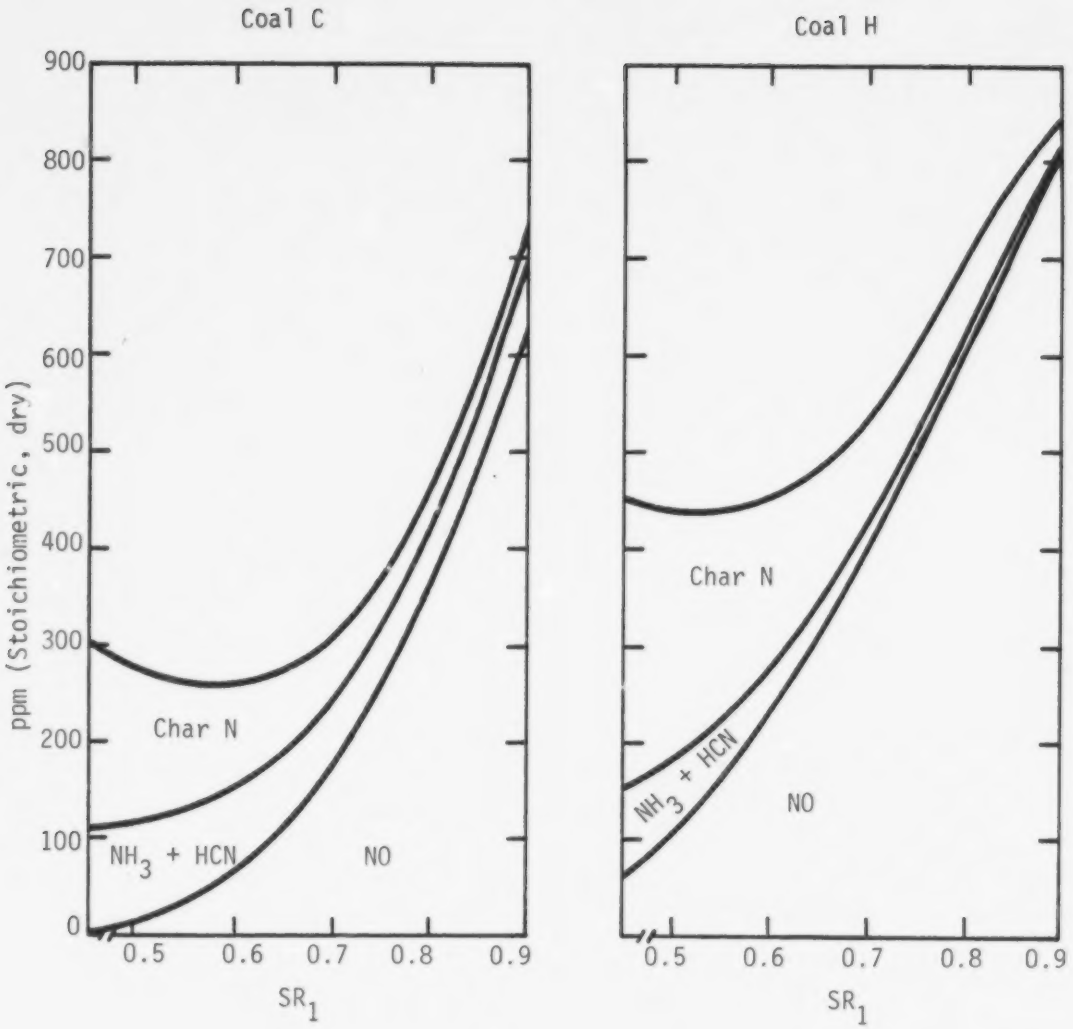

Figure 35. Predicted Conversion of XN and Char N to NO.

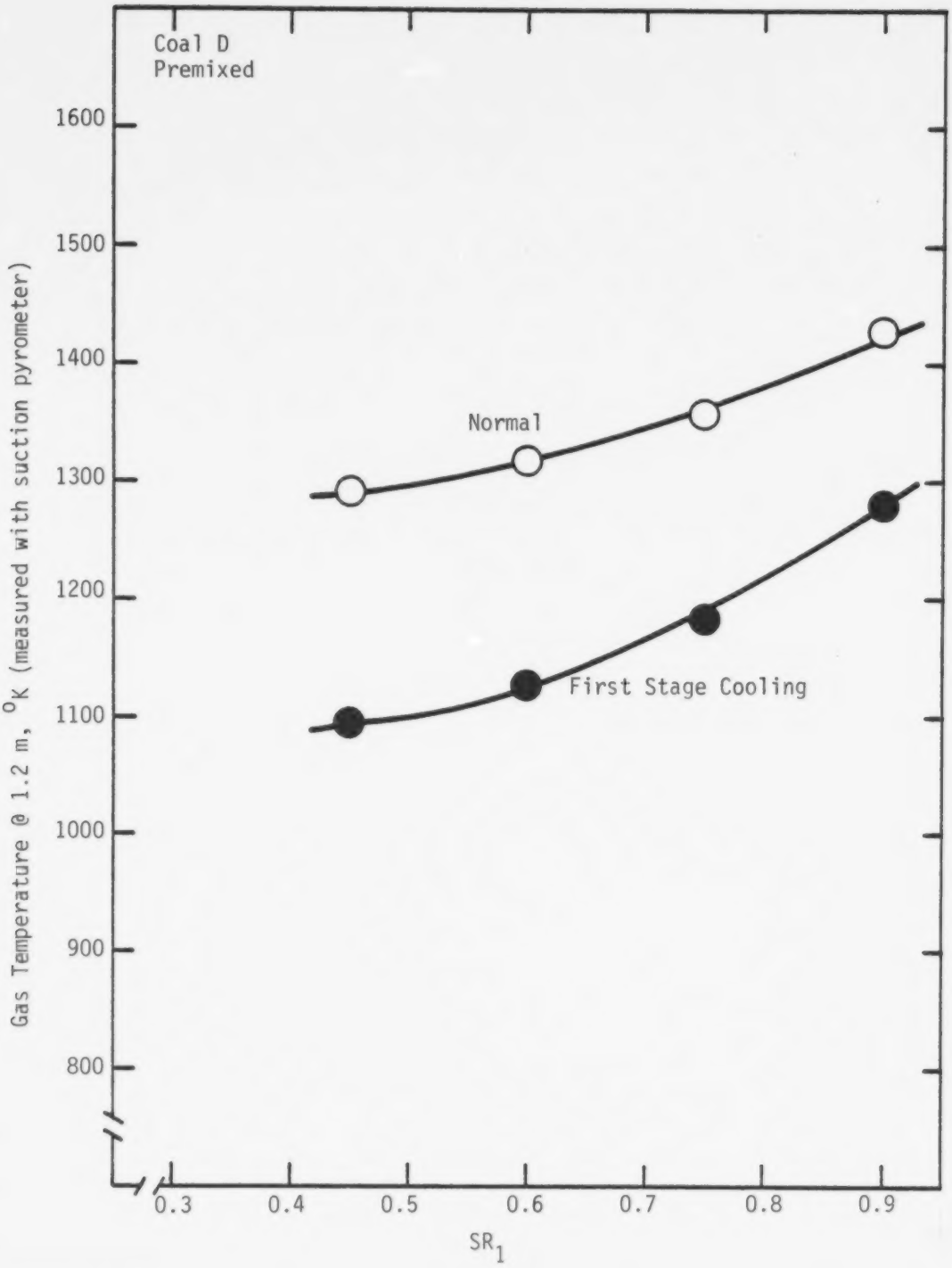

Figure 36. Influence of Cooling on Gas Temperature at First-Stage Exit.

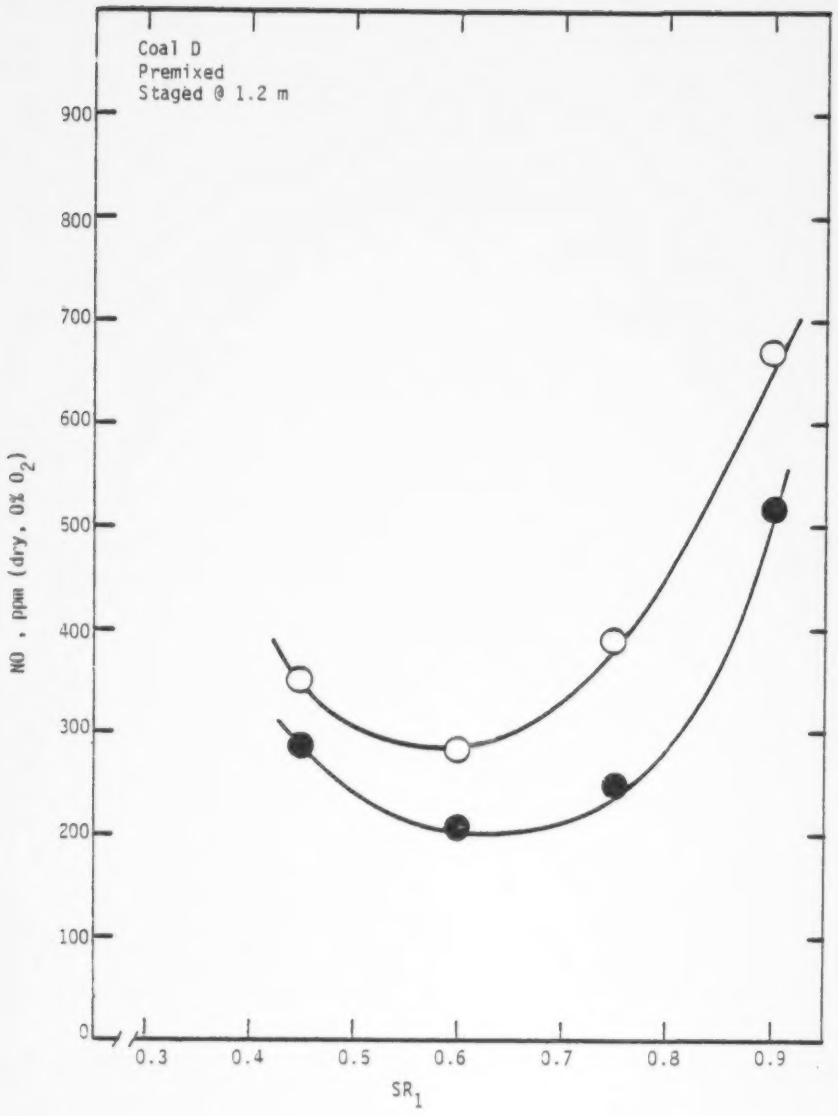

Figure 37. Influence of Cooling on NO Emissions Under Staged Combustion Conditions.

all stoichiometries studied. Similar tests were conducted for six of the IEA coals, and these results are contained in Appendix B. The following sections consider the overall mechanisms of this phenomena in terms of first- and second-stage effects. The data shown in Figure 37 are typical of the results obtained for Coal D and Coal N; however, the effect was found to be dependent on fuel composition, as will be described in the final part of this section.

First-Stage Processes

Figure 38 presents data on the impact of the time/temperature history on the gas-phase and solid-phase nitrogen species at the exit of the first stage. These results indicate that for Coal D, increasing the rate of first-stage heat extraction had relatively little effect on the intermediate gas-phase species and on the amount of nitrogen retained in the solid phase. These data suggest that the large reduction in the exhaust emissions (Figure 37) is not due to changes in the "fuel" entering the second stage; rather, it must be the direct result of a major change in the second-stage processes. (Appendix D presents XN and char nitrogen concentrations at the first-stage exit under cooling conditions for six of the IEA coals.)

Solid Nitrogen Conversion

To investigate the influence of first-stage cooling on solid (char) nitrogen conversion, Chen et al (1981) conducted a series of experiments with the COED char/C_3H_8 fuel burning in argon/oxygen. Again, the first-stage exit temperature was decreased approximately 200°K with a wall-cooling coil. Figure 39 shows the temperature and exhaust NO emission results from this test sequence. The emissions data indicate that at SR_1 = 0.9 cooling increased exhaust NO by 37 ppm, and this is directly attributable to a measured increase in first-stage NO of 47 ppm. At lower stoichiometries, no effect was obsered. Thus, it appears that increasing the heat extraction rate does not affect the oxidation of solid-phase nitrogen in the second-stage flame.

TFN Conversion

Chen et al (1981) investigated the influence of first-stage cooling on gas-phase TFN conversion in the second stage by studying staged propane/

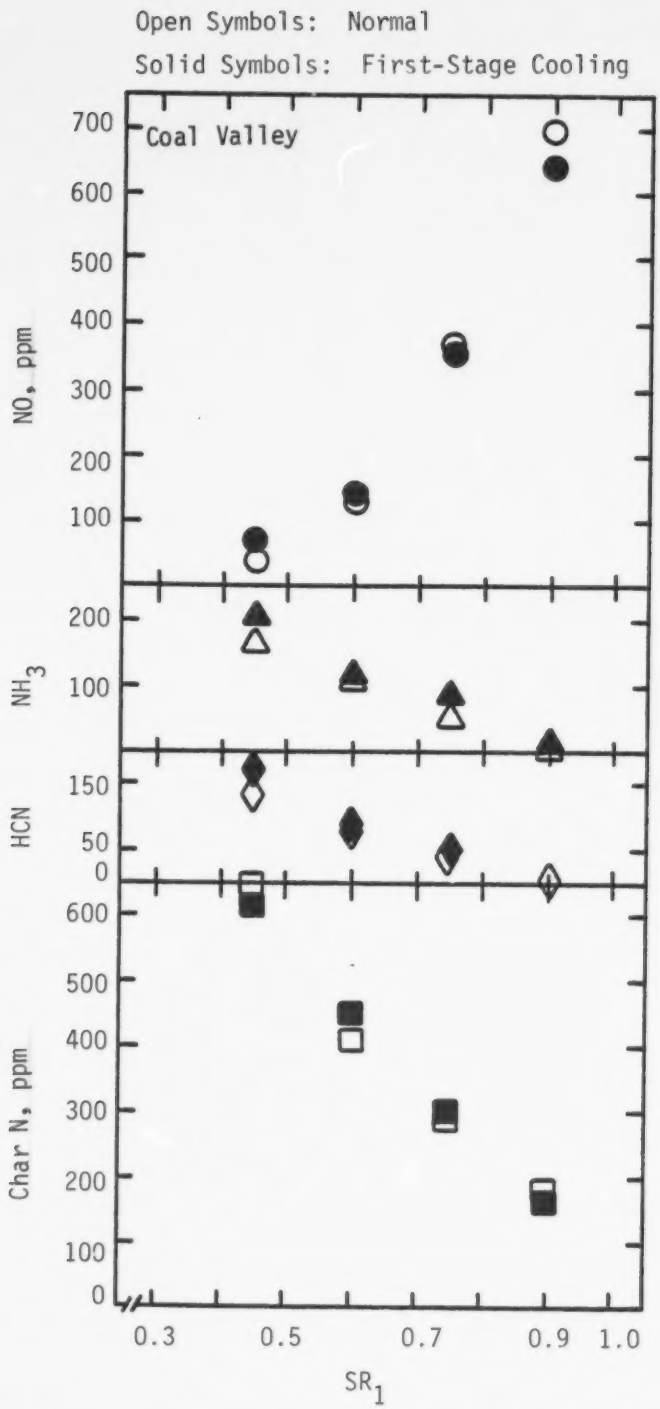

Figure 38. Influence of Cooling on Gas Phase and Solid Phase Nitrogen Concentrations.

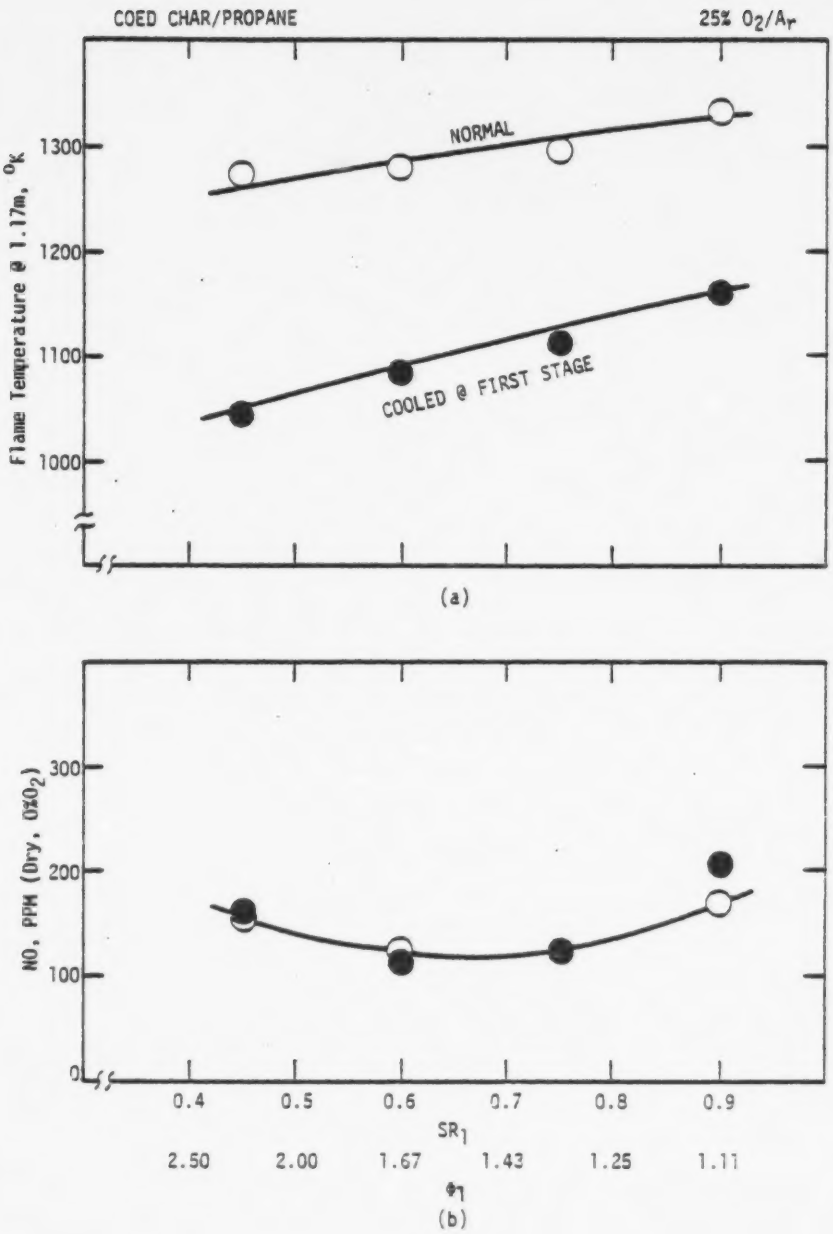

Figure 39. Influence of First Stage Cooling on Solid Nitrogen Conversion.

ammonia flames. Figure 40 summarizes these data and indicates that when the first-stage stoichiometry is relatively lean ($SR_1 \geq 0.75$) and NO is the dominant TFN species, temperature appears to have little effect on second-stage TFN conversion. This is in direct agreement with previous excess air studies on the influence of temperature on fuel nitrogen conversion. However, when HCN and NH_3 are the dominant species under richer conditions, decreasing the temperature of the second-stage flame (by cooling in the first stage) dramatically decreased TFN conversion. In these experiments, there was no solid phase, so this effect must have been associated with a change in gas-phase chemistry. Because the propane/NH_3 results (Figure 40) suggested that the form of the TFN species was of primary importance, Chen and co-workers conducted a special series of experiments with the Utah coal. Alternatively, NO or NH_3 was injected into the second-stage flame (with the staging air) and the effect of cooling was studied. These results are summarized in Figure 41. When the added fuel nitrogen was in the form of NO (circles), the thermal environment had essentially no effect on the conversion (retention) of the fuel nitrogen in the second-stage flame. However, when NH_3 was added, a significant thermal effect was observed at all stoichiometries (triangles). These results strongly suggest that the reduction in exhaust NO emissions with increased heat extraction is directly associated with selective reduction of first-stage NO by NH_3 in the second-stage flame. The concentrations and thermal conditions are essentially analogous to those required for external "thermal de-NO_x" (Lyon, 1979).

Coupling With Fuel Chemistry

Figure 42 shows the influence of heat extraction rate on the lignite Coal A and these data are typical of that obtained with all of the lignite and sub-bituminous coals (including Coal C and Coal B). With the low rank coals, increasing the rate of heat extraction in the first stage resulted in significant reductions of exhaust NO emissions at relatively high stoichiometries ($SR_1 > 0.7$); however, it had little effect under extremely fuel-rich conditions. Figure 43 shows the results of the detailed in-flame concentration measurements at the end of the first stage for the Coal A lignite. In general, the increased cooling had little effect on the total gas phase nitrogen species (NO + HCN + NH_3); however, at very rich conditions

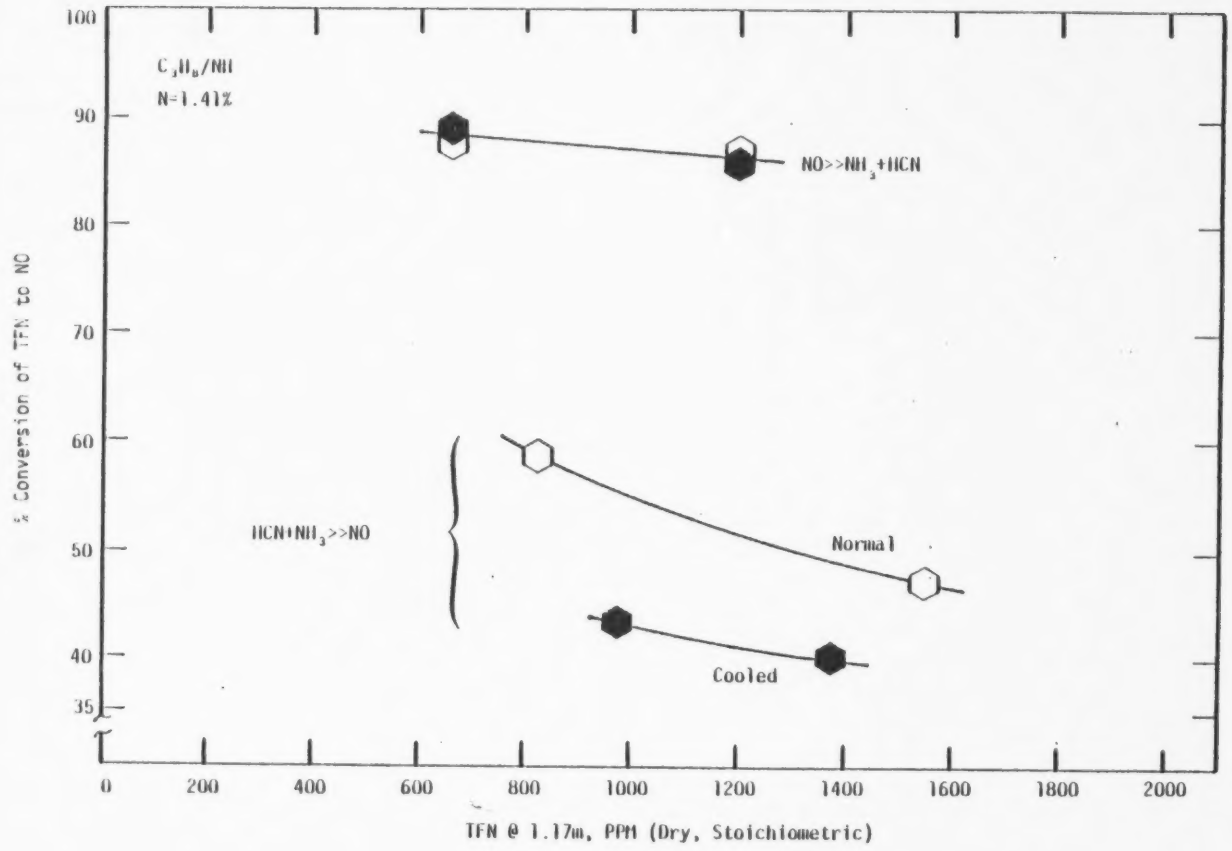

Figure 40. Influence of Cooling on Second Stage TFN Conversion - C_3H_8/NH_3 Flames.

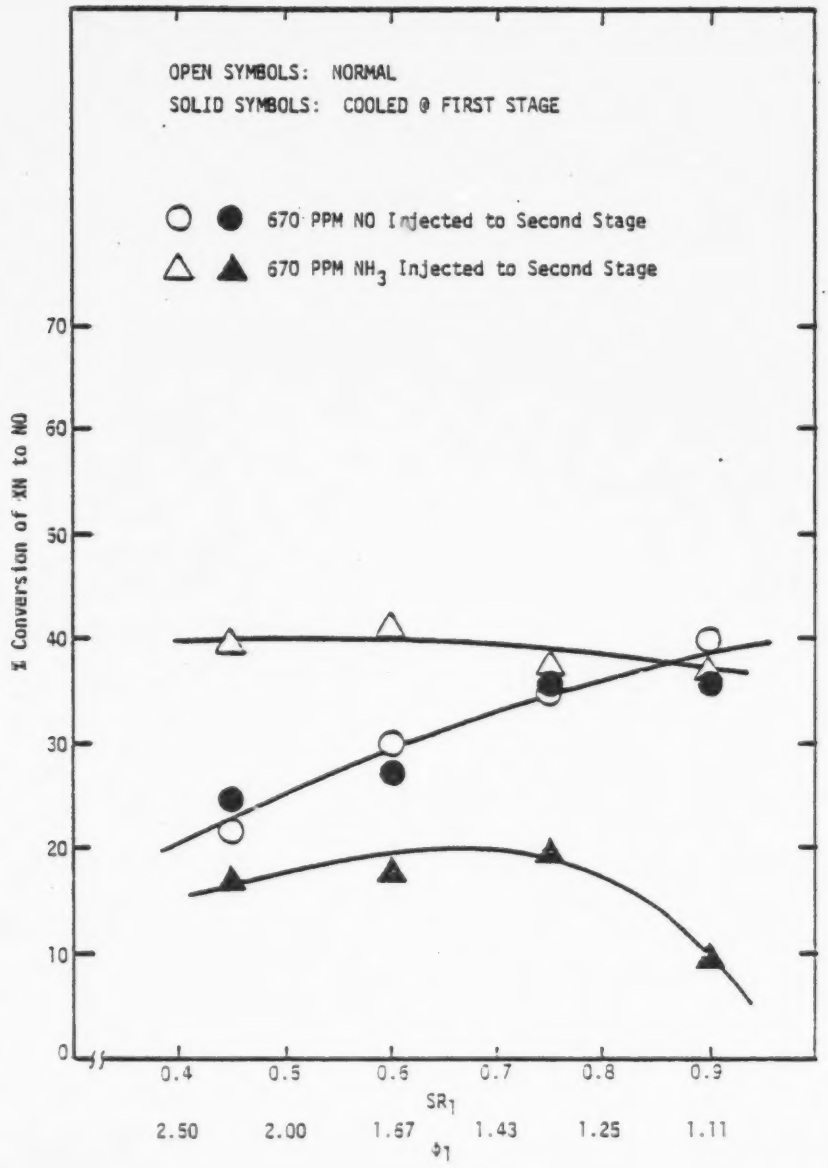

Figure 41. Influence of Cooling on Second Stage TFN Conversion - Utha Coal Flames.

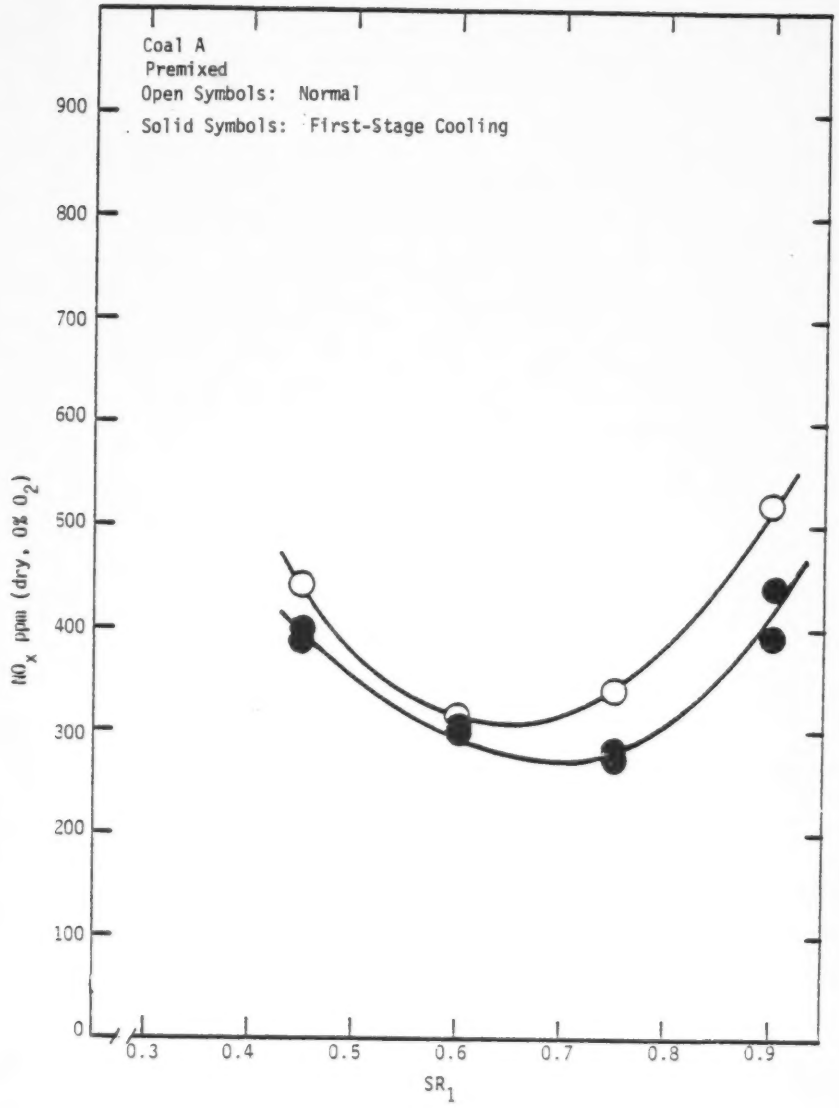

Figure 42. Influence of Cooling on NO Emissions Under Staged Combustion Conditions.

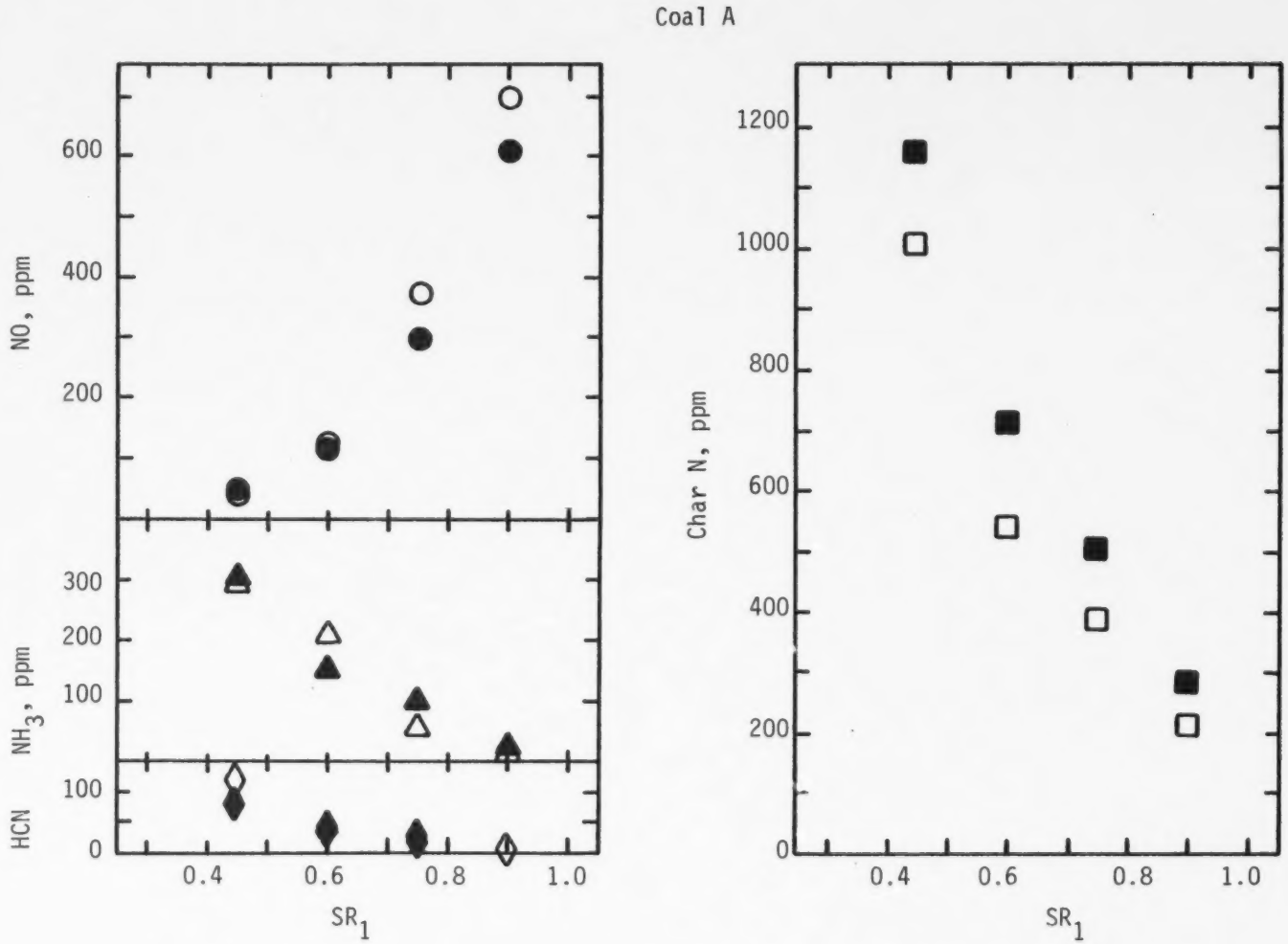

Figure 43. Influence of Cooling on XN and Char N Concentrations.

(SR_1 < 0.7) the cooling resulted in significant increases in the solid nitrogen carried into the second stage. Thus, the emission reduction associated with decreasing the second-stage temperature to the point where NH_3 could selectively reduce NO, appears to have been somewhat mitigated by an increase in solid-phase nitrogen carry-through.

Figure 44 shows similar results for the high volatile bituminous Coal I, and these data are typical of those obtained with the other high volatile coals (Coal M, Coal P, and Utah). Figure 45 shows the corresponding in-flame measurements for Coal I and indicates that, at high stoichiometric ratios (SR_1 > 0.7), reducing the temperature of the first-stage increases the concentration of NO exiting the first stage. This is believed to be directly attributable to a decrease in the rate of NO decay in the first stage. In addition, the internal measurements show that, at high stoichiometries, there is essentially no NH_3 exiting the first stage. Thus, it is not surprising that the exhaust measurements (Figure 44) indicate that at stoichiometric ratios greater than 0.7 there is essentially no effect of increasing the heat extraction rate.

Figure 46 summarizes all of the data obtained with the IEA coals on the influence of thermal environment. The upper plot indicates the change in NO_x emissions (at a stoichiometric ratio of 0.75) when the second stage flame temperature was decreased by approximately 200°K. (A negative change implies that the emissions decreased with increased cooling.) As noted previously, the low rank coals exhibited the greatest decrease in NO_x emissions. These coals had relatively large amounts of NH_3 leaving the first stage, and increased first-stage cooling had only a small influence on first-stage NO and char nitrogen carry-through. However, in the case of the high nitrogen, high volatile bituminous Coal I, increased first-stage heat extraction actually increased the exhaust NO_x emissions at a stoichiometric ratio of 0.75. This appears to be because the gases exiting the first-stage contained essentially no NH_3 and because the increased cooling resulted in a large increase in first-stage NO.

Thus, the optimum heat extraction rate for a two-stage combustion system depends heavily on the type of fuel being burned (and on a residence time available). Decreasing the temperature of the second-stage flame zone so that

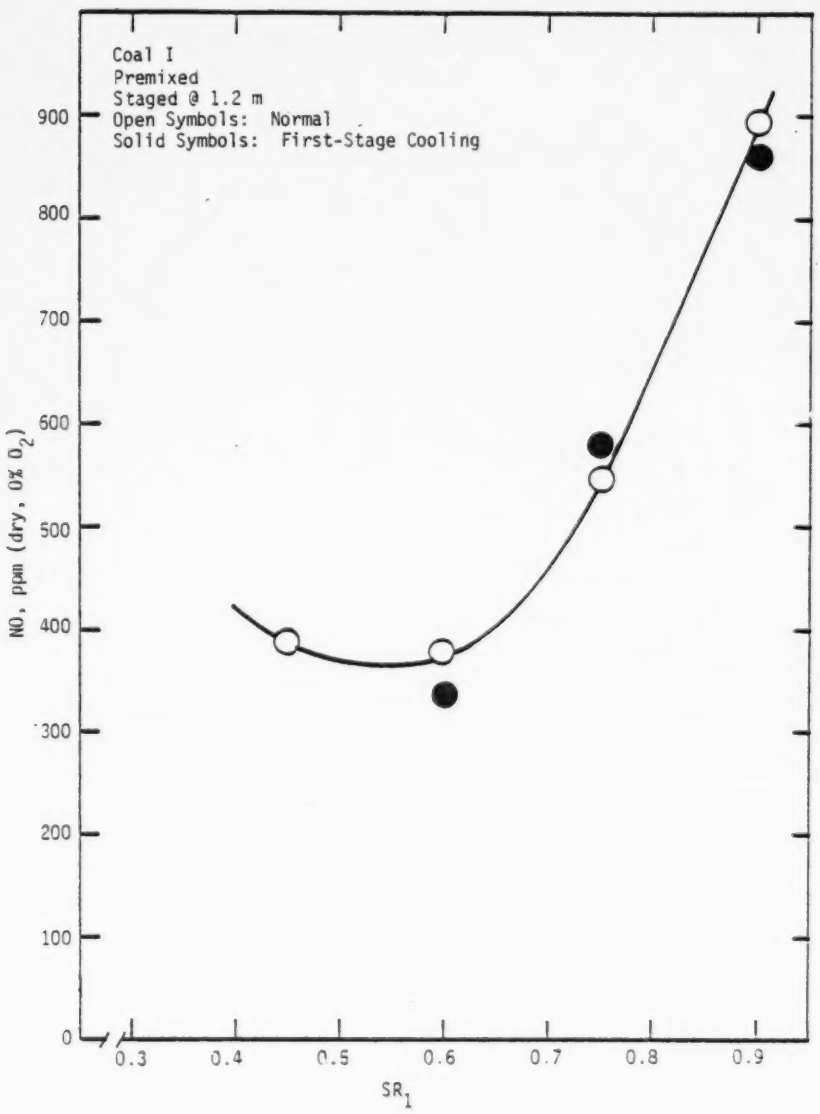

Figure 44. Influence of Cooling on NO Emissions.

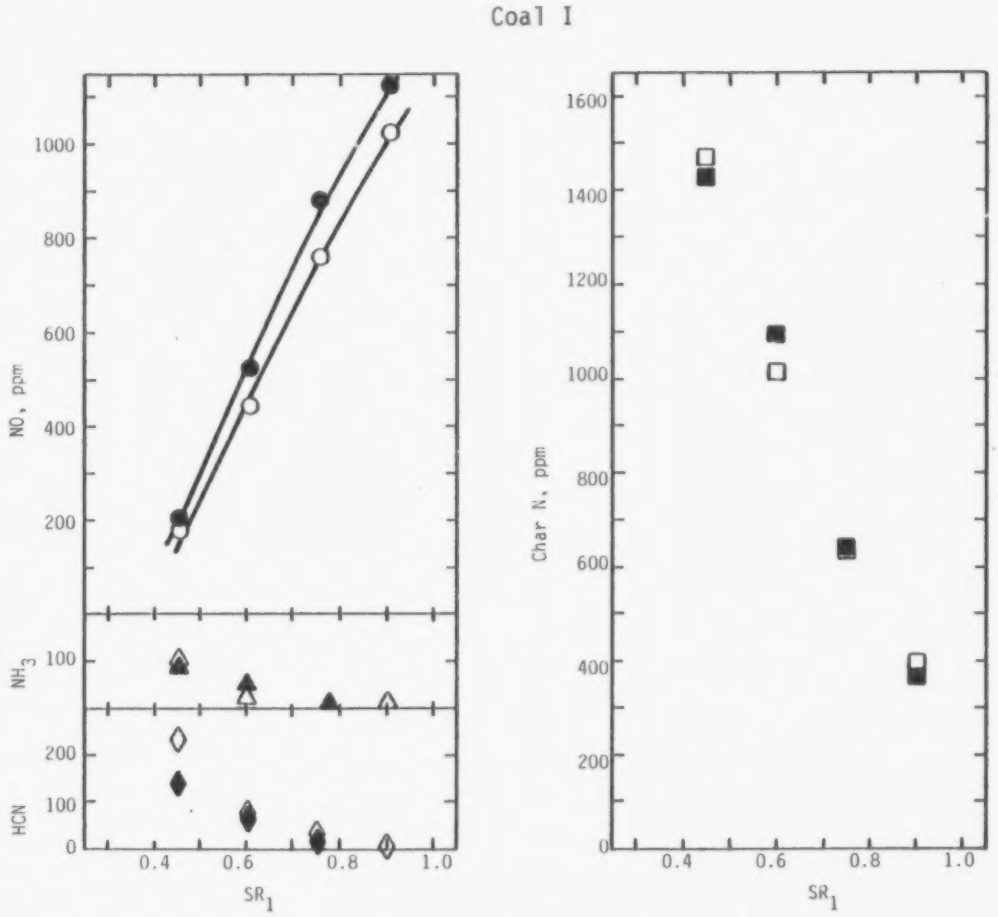

Figure 45. Influence of Cooling on XN and Char N Concentrations.

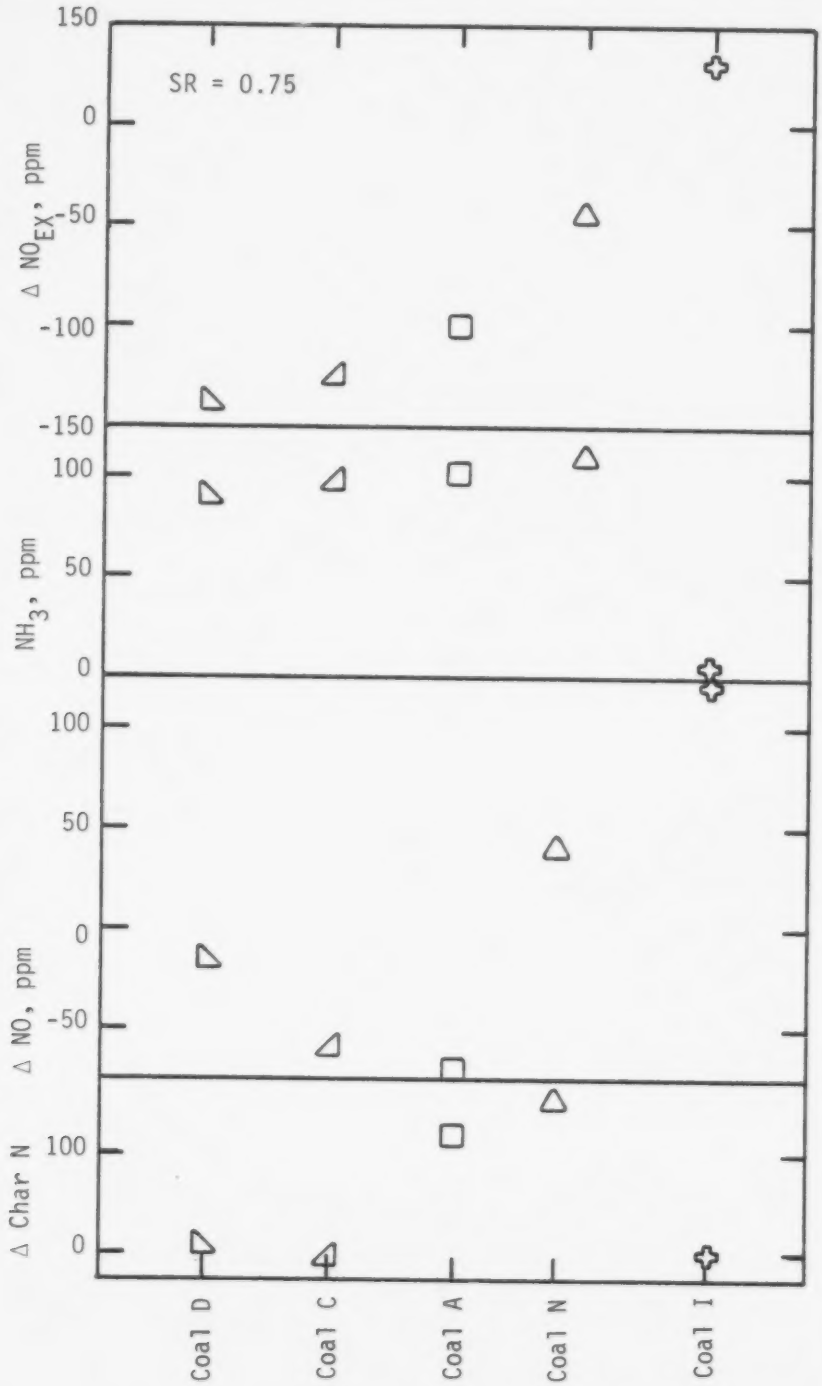

Figure 46. Influence of Thermal Environment.

the selective NO + NH_3 reaction will occur, will be most effective with low rank fuels which produce large amounts of NH_3 under staged conditions and with fuels which do not tend to carry a considerable amount of solid nitrogen into the second stage.

It should be noted, however, that heat extraction from the primary zone can introduce practical problems because of reduced carbon burnout. Table 2 shows the percent carbon burnout, based on flue CO_2 measurements, for three of the non-U.S. coals tested with first stage cooling under staged combustion conditions.

TABLE 2. PERCENT CARBON BURNOUT (FIRST STAGE COOLING, SR_t = 1.25)

SR_1 \ Fuel	Coal D	Coal A	Coal I
0.9	96%	97%	90%
0.75	94%	96%	83%
0.6	93%	95%	76%
0.45	93%	93%	69%

6.0 CONCLUSIONS

Fuel NO formed during the combustion of pulverized coal can be isolated by replacing the combustion air with an artificial oxidant mixture containing carbon dioxide, argon, and oxygen. It appears that under conditions typical of commercial practice, oxidation of nitrogen chemically bound in the coal is the major source of NO_x emissions. Tests with 20 non-U.S. coals under excess air conditions indicated that although the nitrogen content of these coals ranged from 0.8 to 2.5 percent (DAF) the emissions correlated generally with those obtained from 28 U.S. coals with a smaller range of nitrogen content. Fuel NO emissions were reduced as the rate of fuel/air mixing was reduced. In general, fuel NO emissions increased with increasing fuel nitrogen content; however, other fuel properties such as hydrocarbon volatile content, and the partition of nitrogen between the char and volatile fractions, were found to be important. In general, coals which evolved large amounts of reactive volatile nitrogen under inert-pyrolysis conditions gave high exhaust emissions with rapidly mixing burners and relatively low exhaust emissions with long axial flames. Conversely, those coals which tend to retain a large fraction of their nitrogen in the solid phase until the char burnout regime tend to produce relatively low NO under well mixed conditions. It was found that the exhaust emissions could be correlated in terms of total fuel-nitrogen content, reactive volatile nitrogen content as determined by inert pyrolysis and nitrogen content of the ASTM char.

Increasing flame temperature and decreasing particle size both increased NO emissions with rapidly mixed flames because both changes enhanced the evolution of fuel-nitrogen from the coal particle. Conversely, with axial diffusion flames, increasing temperature or decreasing particle size was found to be beneficial because both changes promote the evolution of fuel nitrogen species within fuel-rich flame core.

Detailed measurements of first stage and exhaust species concentrations suggest that a staged combustion system must be optimized with respect to first stage stoichiometry and residence time, fuel properties and heat extraction rate. As first stage stoichiometry is decreased, the NO formed in the fuel-rich zone decreases, but other oxidizable gaseous nitrogen species increase as does nitrogen retention in the solid phase material exiting the

first stage. Total fixed-nitrogen (TFN = NO + NH_3 + HCN) generally increases with increasing fuel nitrogen and correlates well with fuel-nitrogen. Increasing the residence time in the fuel-rich stage allows TFN species to decay toward low equilibrium values and thus reduces NO emissions.

The distribution of the TFN species leaving the first stage is strongly dependent upon the coal composition. Of the 9 coals tested in detail, none produced the high HCN concentrations previously observed with the Utah and Texas lignite coals from the United States. The medium volatile bituminous Coal H formed essentially no NH_3 and very little HCN, even under extremely fuel-rich conditions. This behavior was directly analogous to that observed previously with a low volatile Pennsylvania anthracite and with coal chars. In general, the first stage NO percentage decreased significantly with decreasing coal rank from bituminous to lignite. Conversely, the relative importance of NH_3 grew with decreasing rank. In general, HCN was greater than NH_3 with the bituminous coals, but less than NH_3 with all of the subbituminous and lignite coals.

Second stage TFN conversion decreases as the TFN distribution shifts in favor of HCN and NH_3 and as the hydrocarbon content of the second stage reactants increases. The percentage conversion of char nitrogen to NO in the second stage is low (less than 20 percent) and appears to be inversely proportional to the first stage stoichiometric ratio. Exhaust emissions can be correlated in terms of the gas-phase TFN and the char nitrogen entering the second stage.

Increasing the rate of heat extraction from a staged combustion system generally reduces exhaust NO emissions via a complex mechanism. Reduced second stage flame temperatures had little effect on solid-phase nitrogen conversion, but they dramatically decrease gas-phase TFN conversion due to a shift in controlling flame chemistry. If the reactants are cooled sufficiently to bring the bulk gas temperature at the first stage exit to approximately 1200°K, it is possible to obtain selective NO reduction (by NH_3) in the second stage flame zone and therefore reduce the exhaust NO emissions. However, the effectiveness of this concept is strongly dependent on the combustor design (first stage temperature profile and residence time) and fuel chemistry. Increasing heat extraction appears to be most favorable

with low-rank coals, because they produce large amounts of NH_3 and relatively less first stage NO. Conversely, high rank coals (Coal I) may be less influenced by the cooling in the first stage because they produce relatively little NH_3. Additionally, first stage cooling may decrease the rate of TFN decay in the fuel-rich zone and, hence, increase both the TFN and char nitrogen carry-through into the second stage. Finally, because of the extremely low temperatures required for the selective NO + NH_3 reaction, carbon burnout in the second stage may be a significant problem.

REFERENCES

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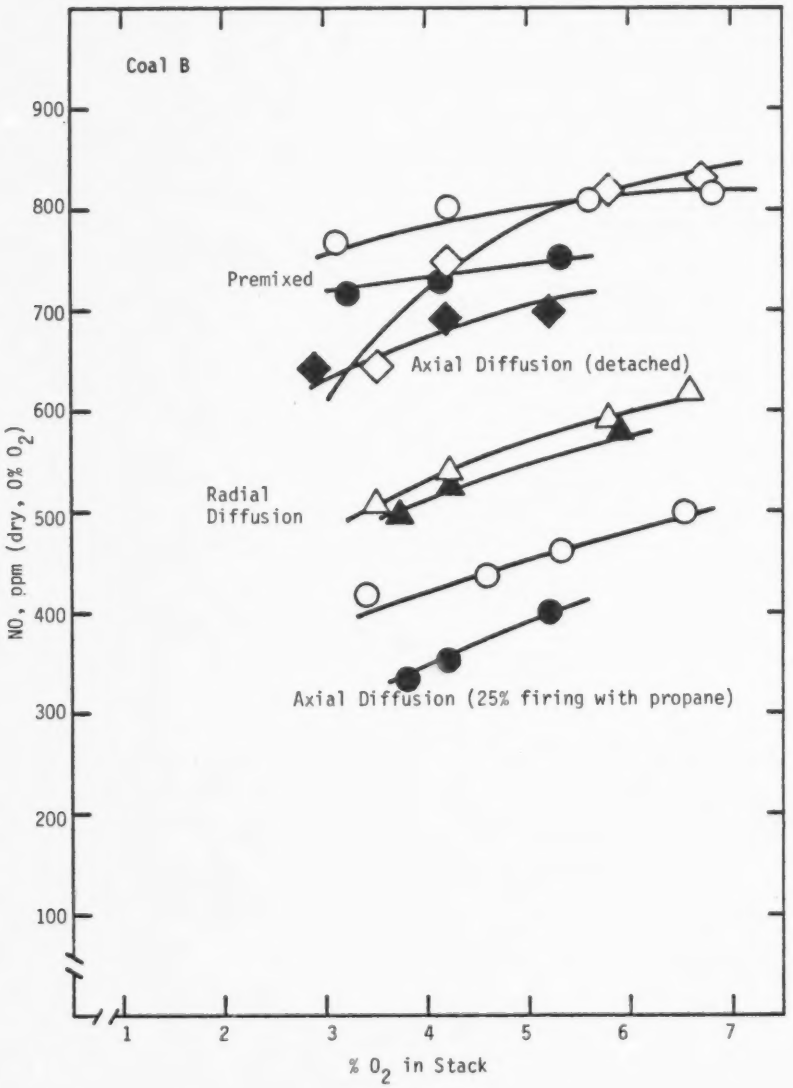
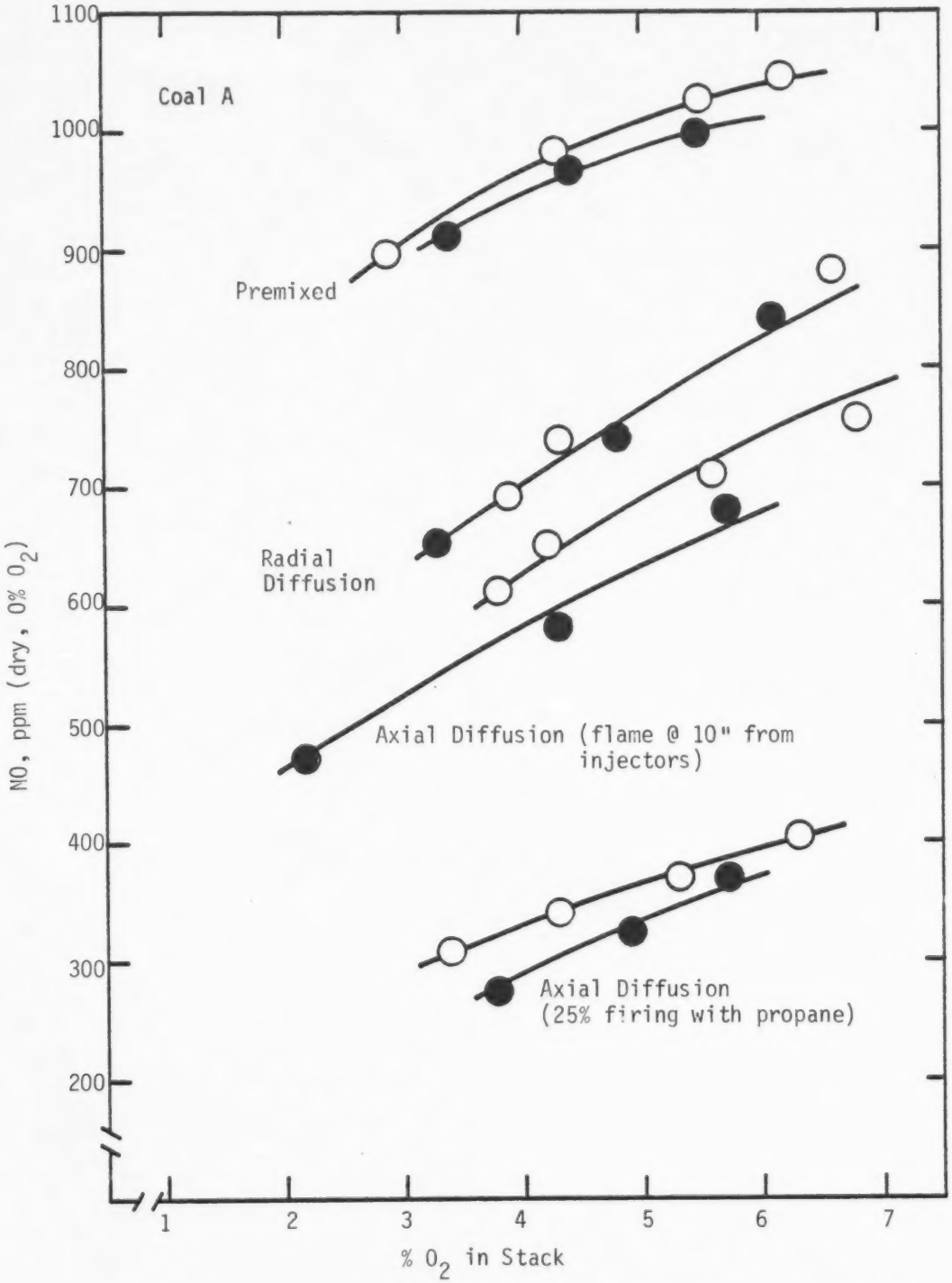
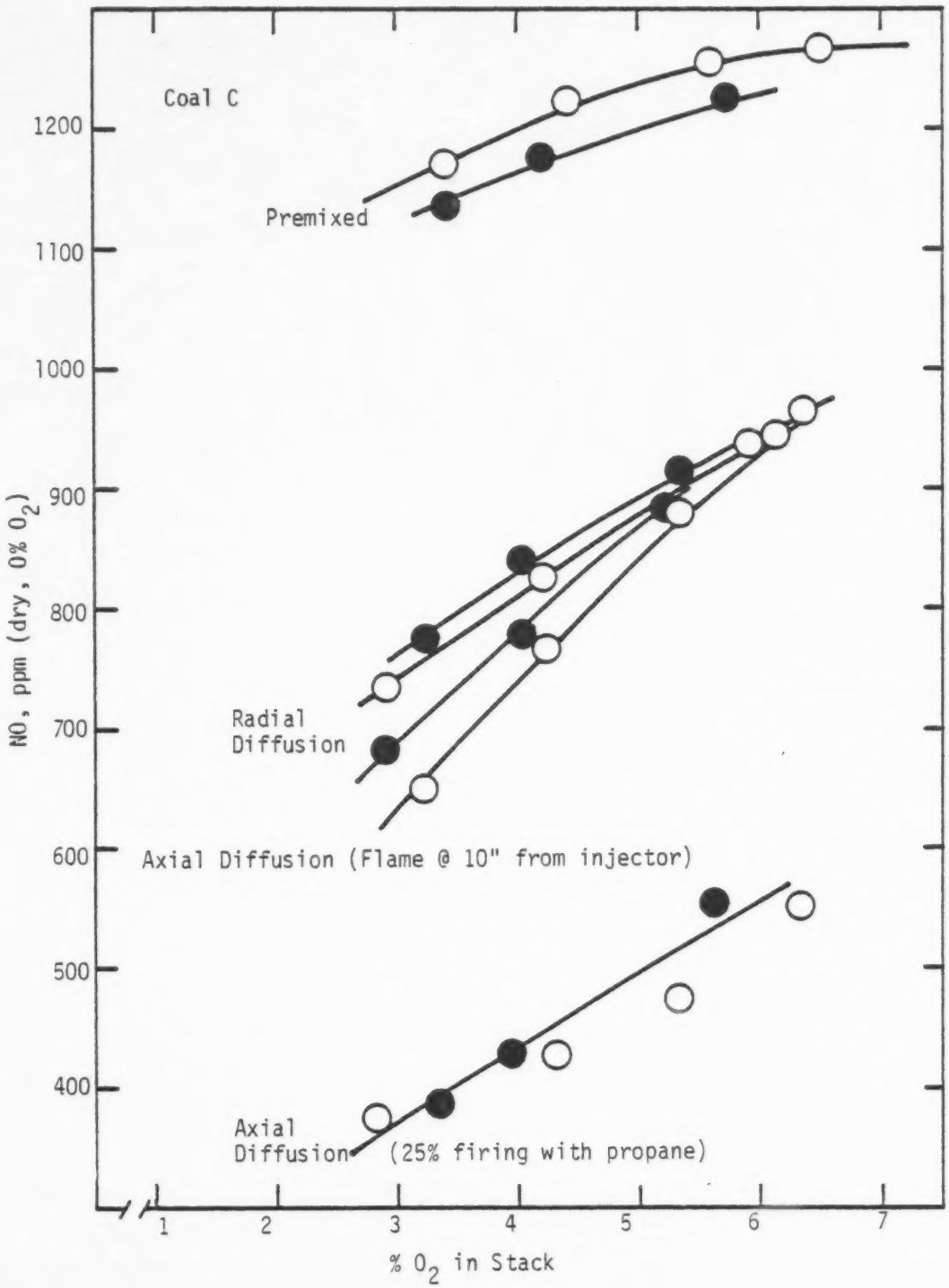
APPENDIX A

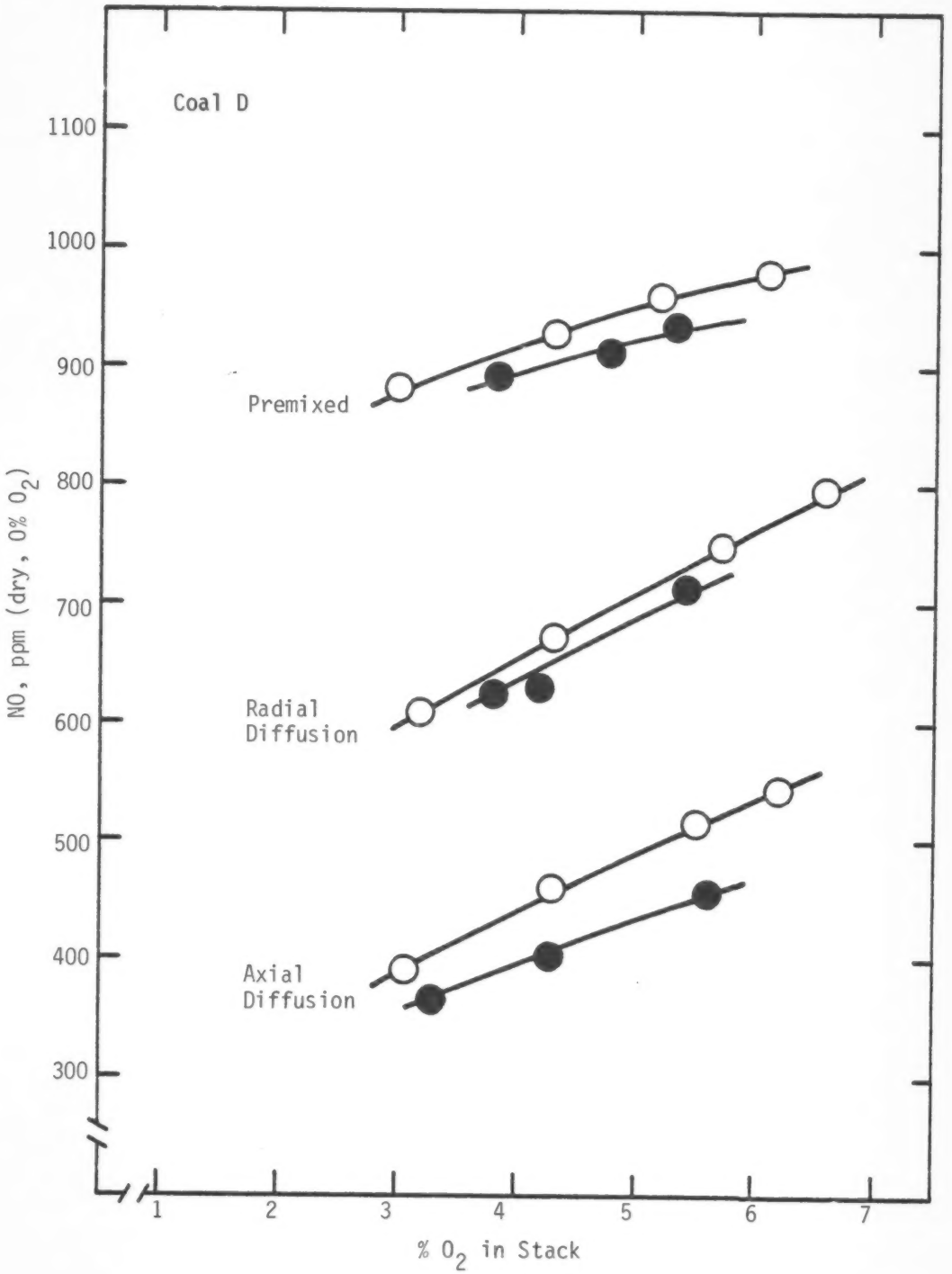
Total and Fuel NO Emissions as a Function of Excess Air and Burner Type

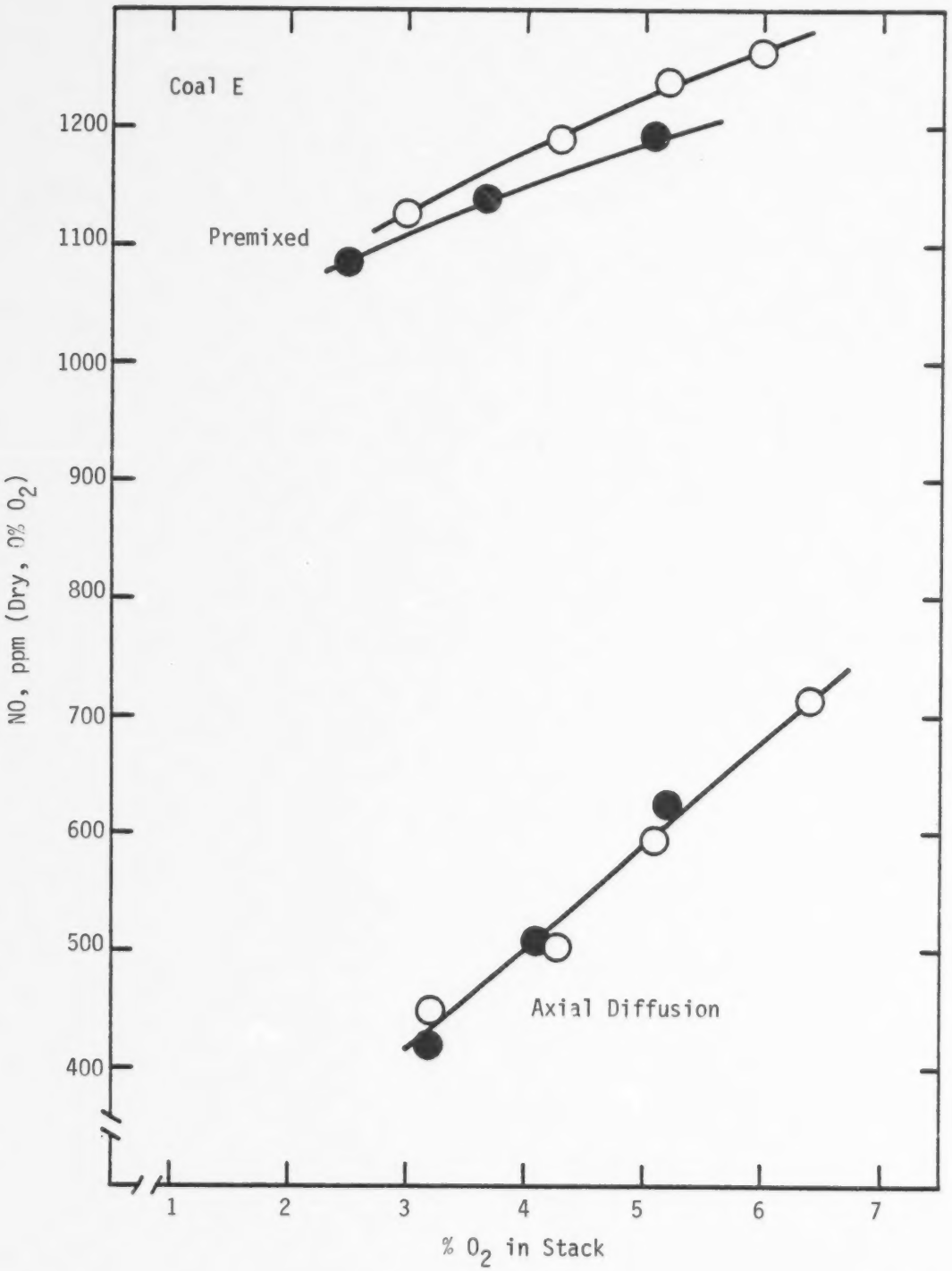
(Open Symbols: Total NO
Solid Symbols: Fuel NO)

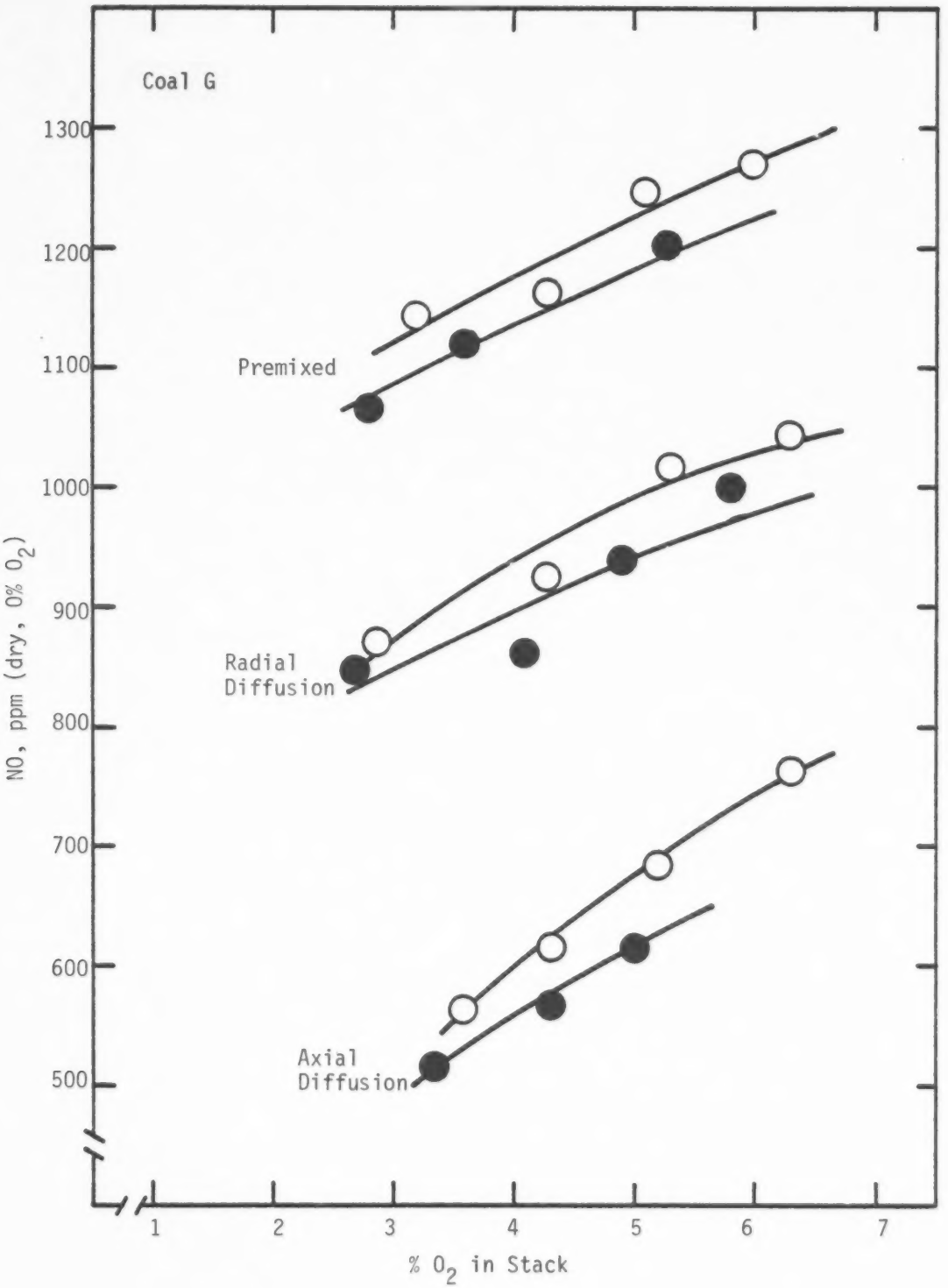


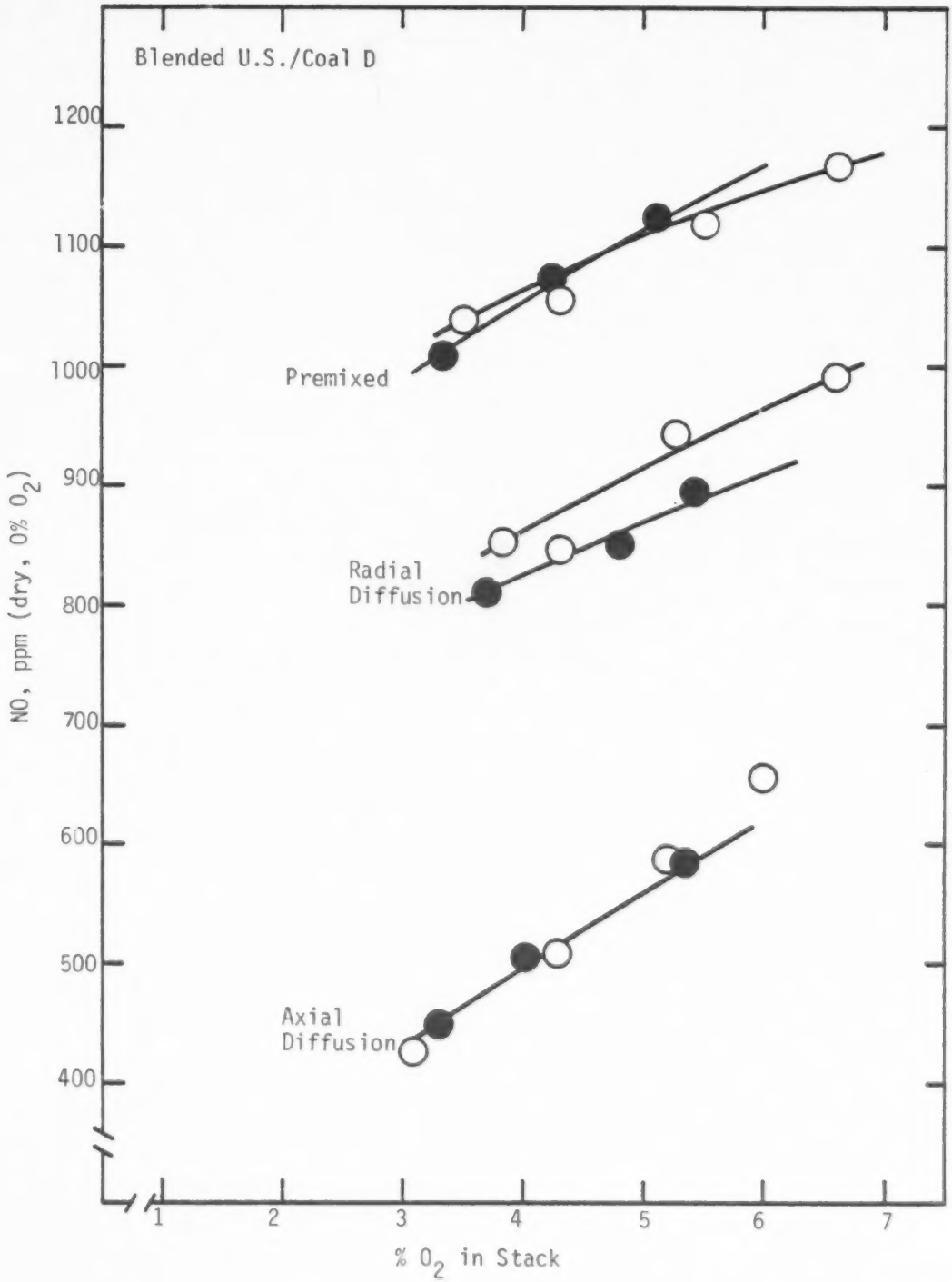

Coal A
Premixed
Radial
Diffusion
Axial Diffusion (flame @ 10" from
injectors)
Axial Diffusion
(25% firing with propane)
NO, ppm (dry, 0% O_2)
% O_2 in Stack
1100
1000
900
800
700
600
500
400
300
200
1
2
3
4
5
6
7

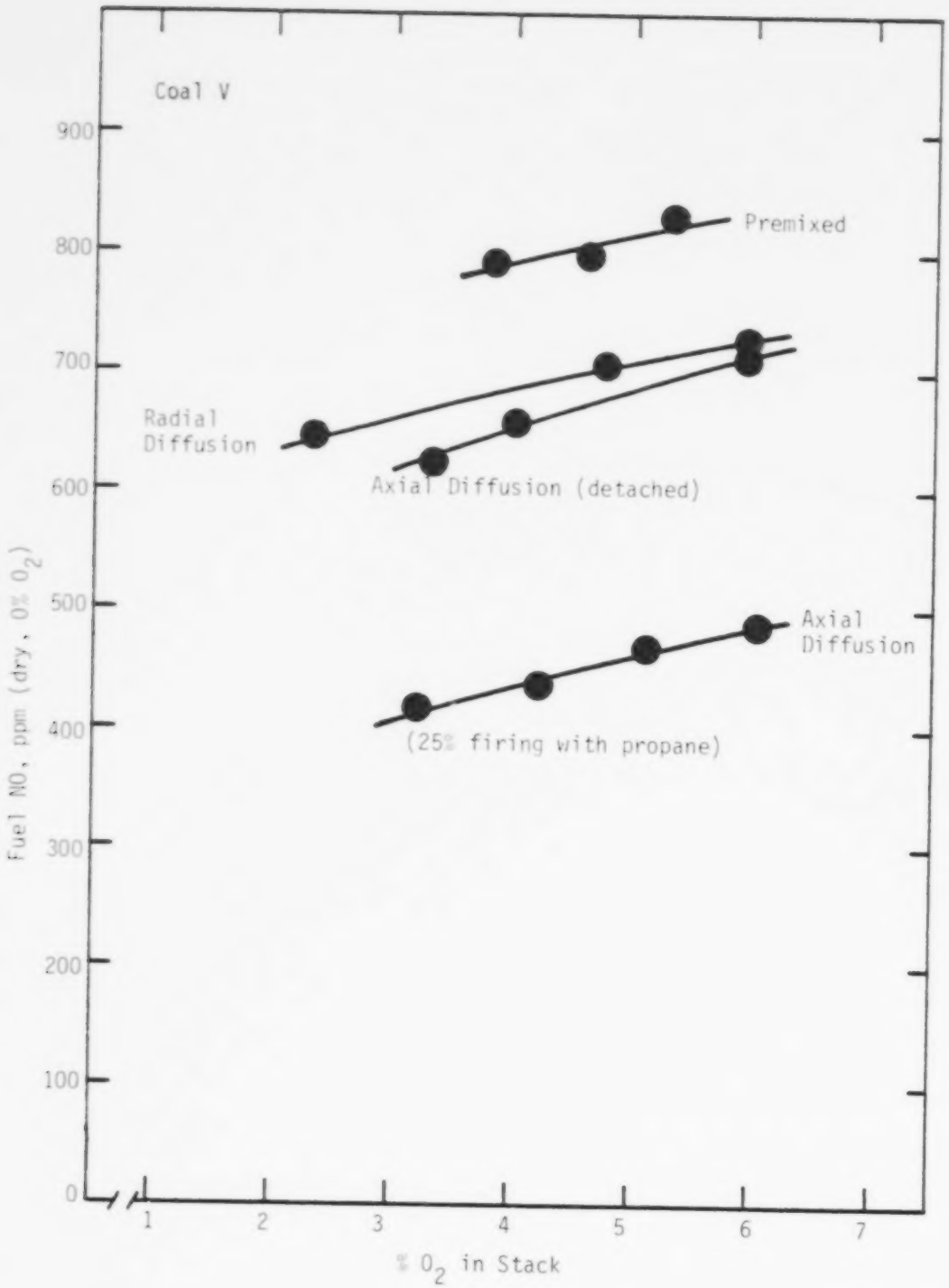

Coal C
Premixed
Radial
Diffusion
Axial Diffusion (Flame @ 10" from injector)
Axial
Diffusion
(25% firing with propane)
NO, ppm (dry, 0% O_2)
1200
1100
1000
900
800
700
600
500
400
1
2
3
4
5
6
7
% O_2 in Stack

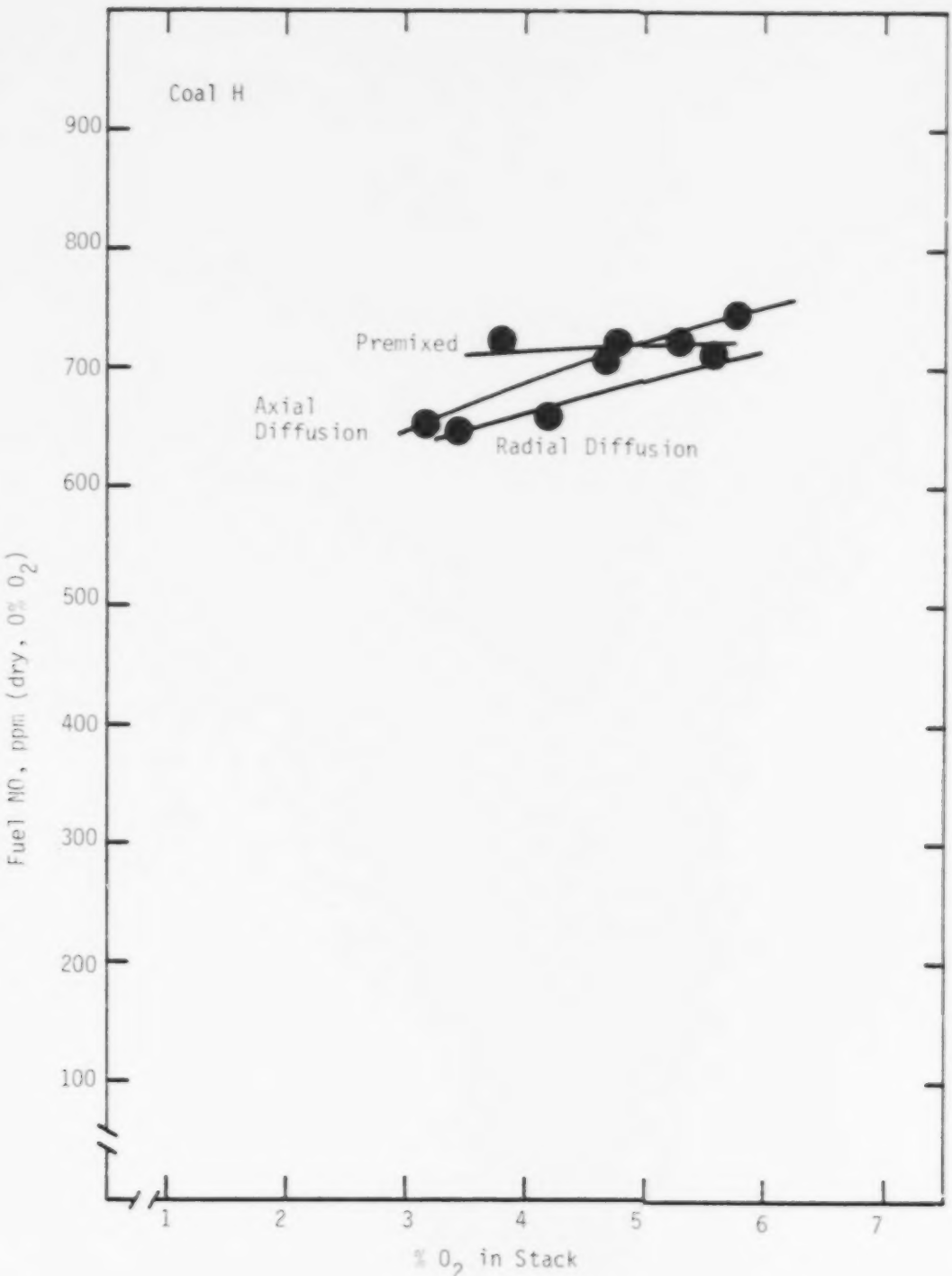

Coal D
1100
1000
900
800
700
600
500
400
300
NO, ppm (dry, 0% O_2)
Premixed
Radial
Diffusion
Axial
Diffusion
1
2
3
4
5
6
7
% O_2 in Stack

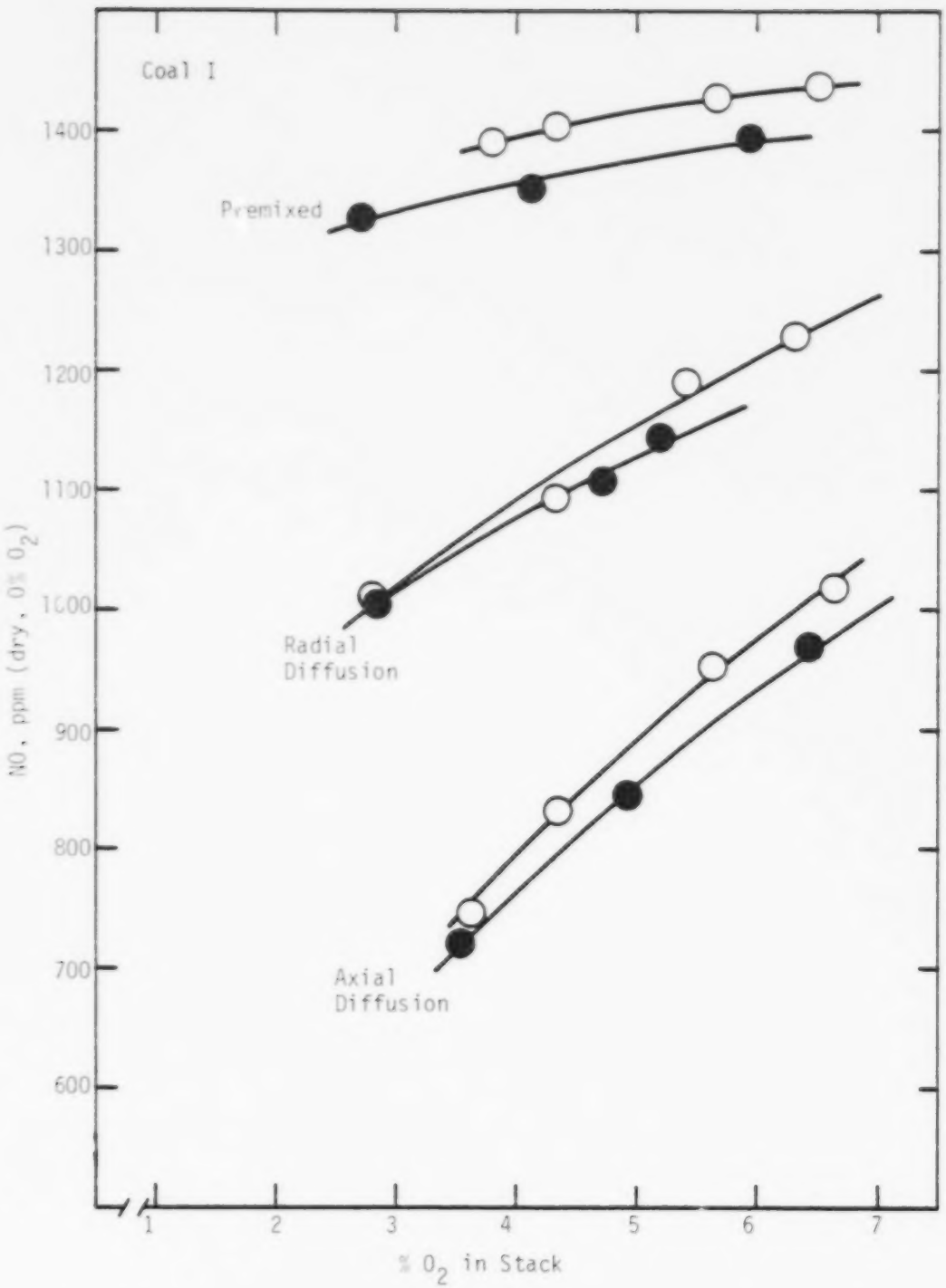

Coal E
Premixed
Axial Diffusion
NO, ppm (Dry, 0% O_2)
% O_2 in Stack
1200
1100
1000
900
800
700
600
500
400
1
2
3
4
5
6
7

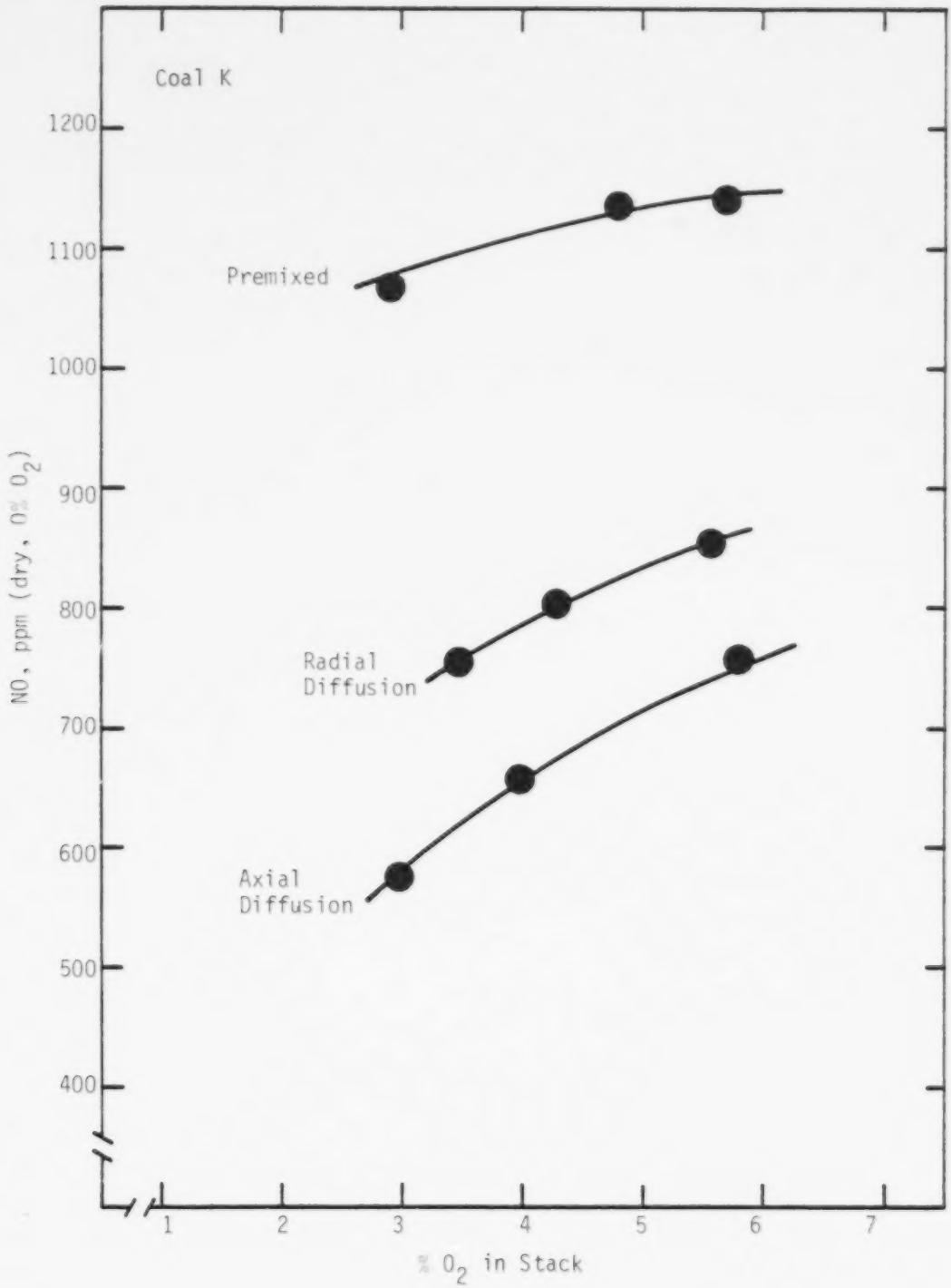

Coal G
1300
1200
1100
1000
900
800
700
600
500
NO, ppm (dry, 0% O_2)
Premixed
Radial
Diffusion
Axial
Diffusion
1
2
3
4
5
6
7
% O_2 in Stack

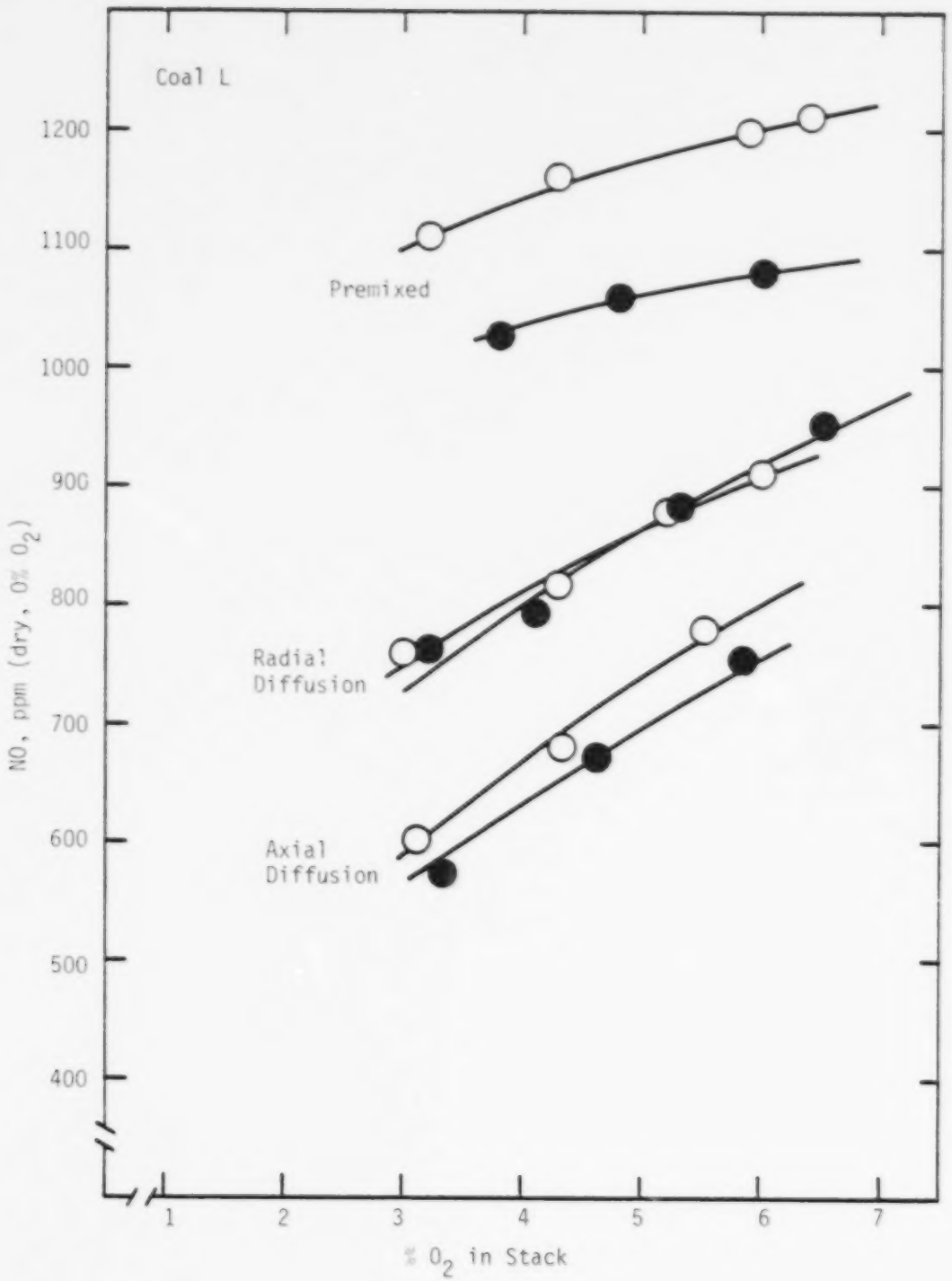

Blended U.S./Coal D
1200
1100
1000
900
800
700
600
500
400
NO, ppm (dry, 0% O_2)
Premixed
Radial
Diffusion
Axial
Diffusion
1
2
3
4
5
6
7
% O_2 in Stack

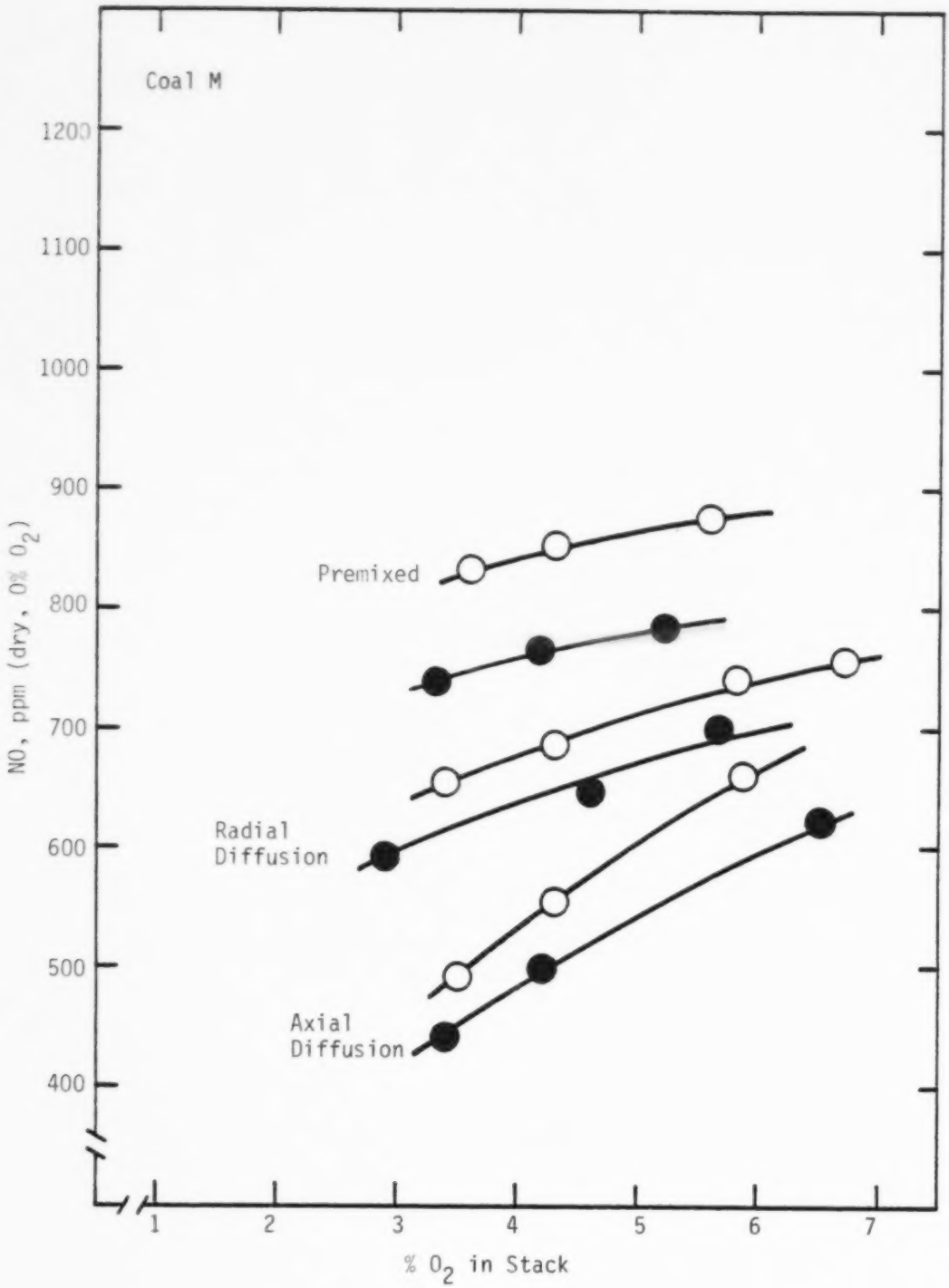

Coal V
900
800
700
600
500
400
300
200
100
0
Premixed
Radial
Diffusion
Axial Diffusion (detached)
Axial
Diffusion
(25% firing with propane)
Fuel NO, ppm (dry, 0% O_2)
1
2
3
4
5
6
7
% O_2 in Stack

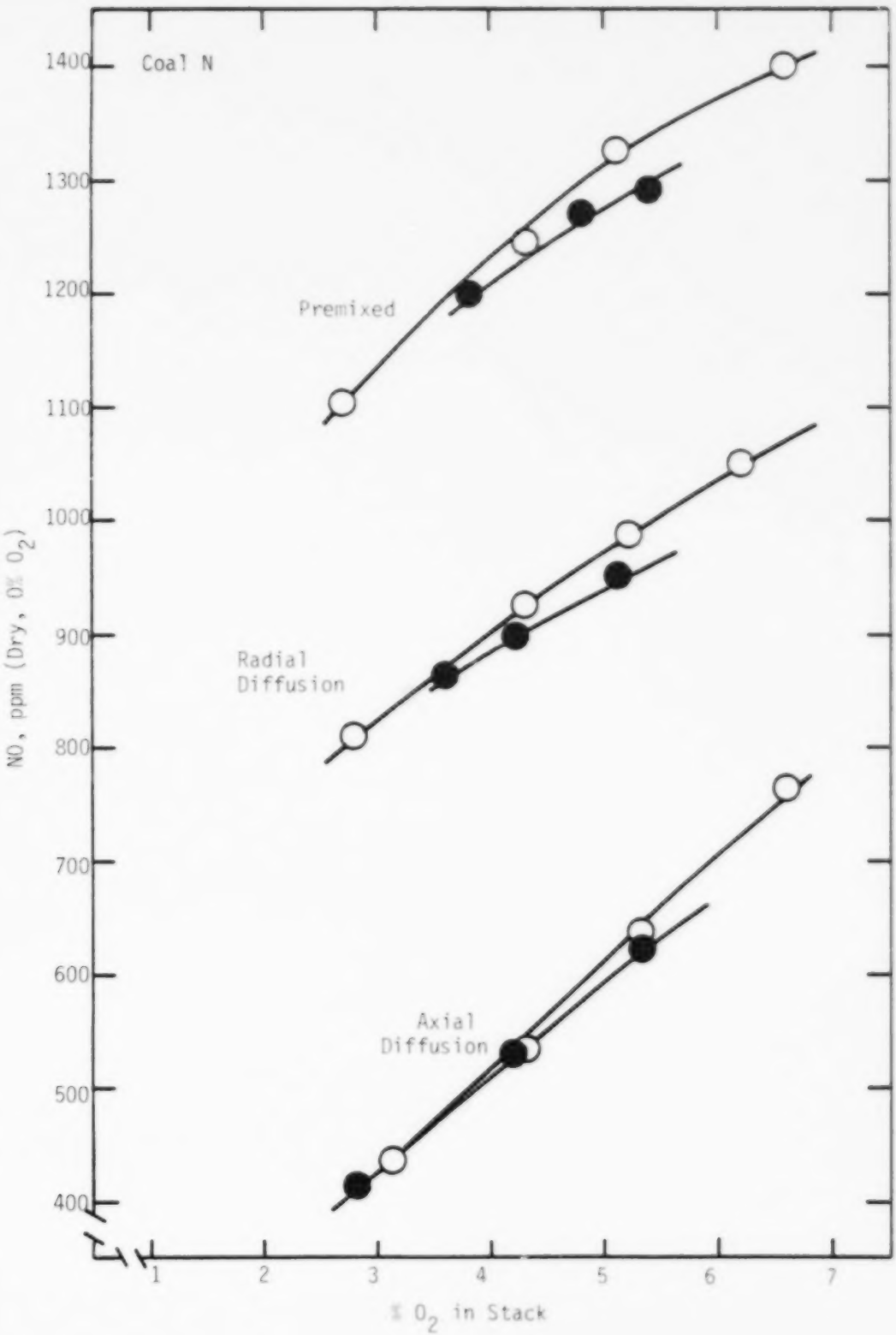

Coal H
900
800
700
600
500
400
300
200
100
Premixed
Axial
Diffusion
Radial Diffusion
Fuel NO, ppm (dry, 0% O_2)
1
2
3
4
5
6
7
% O_2 in Stack

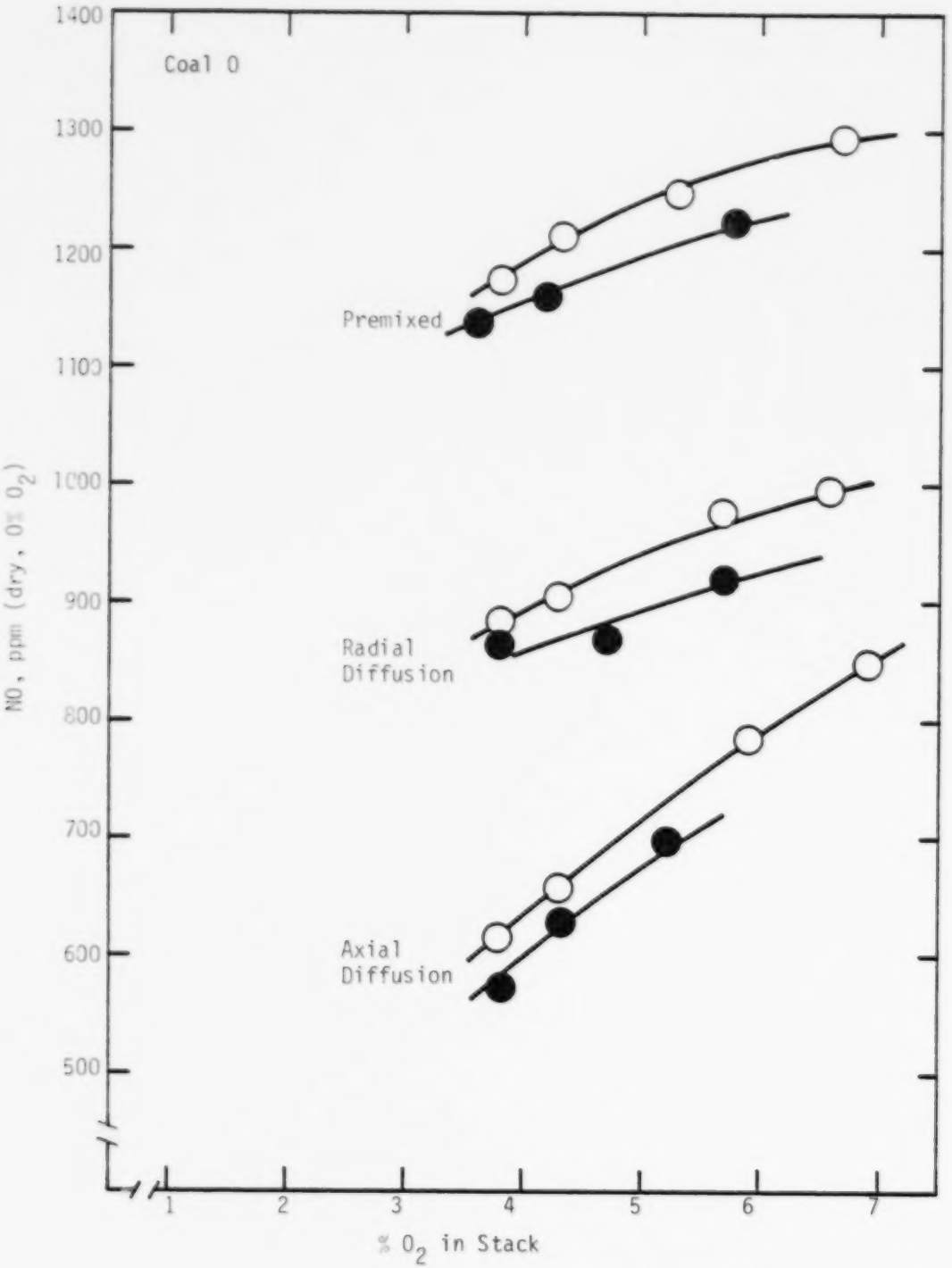

Coal I
Premixed
Radial
Diffusion
Axial
Diffusion
NO, ppm (dry, 0% O_2)
1400
1300
1200
1100
1000
900
800
700
600
1
2
3
4
5
6
7
% O_2 in Stack

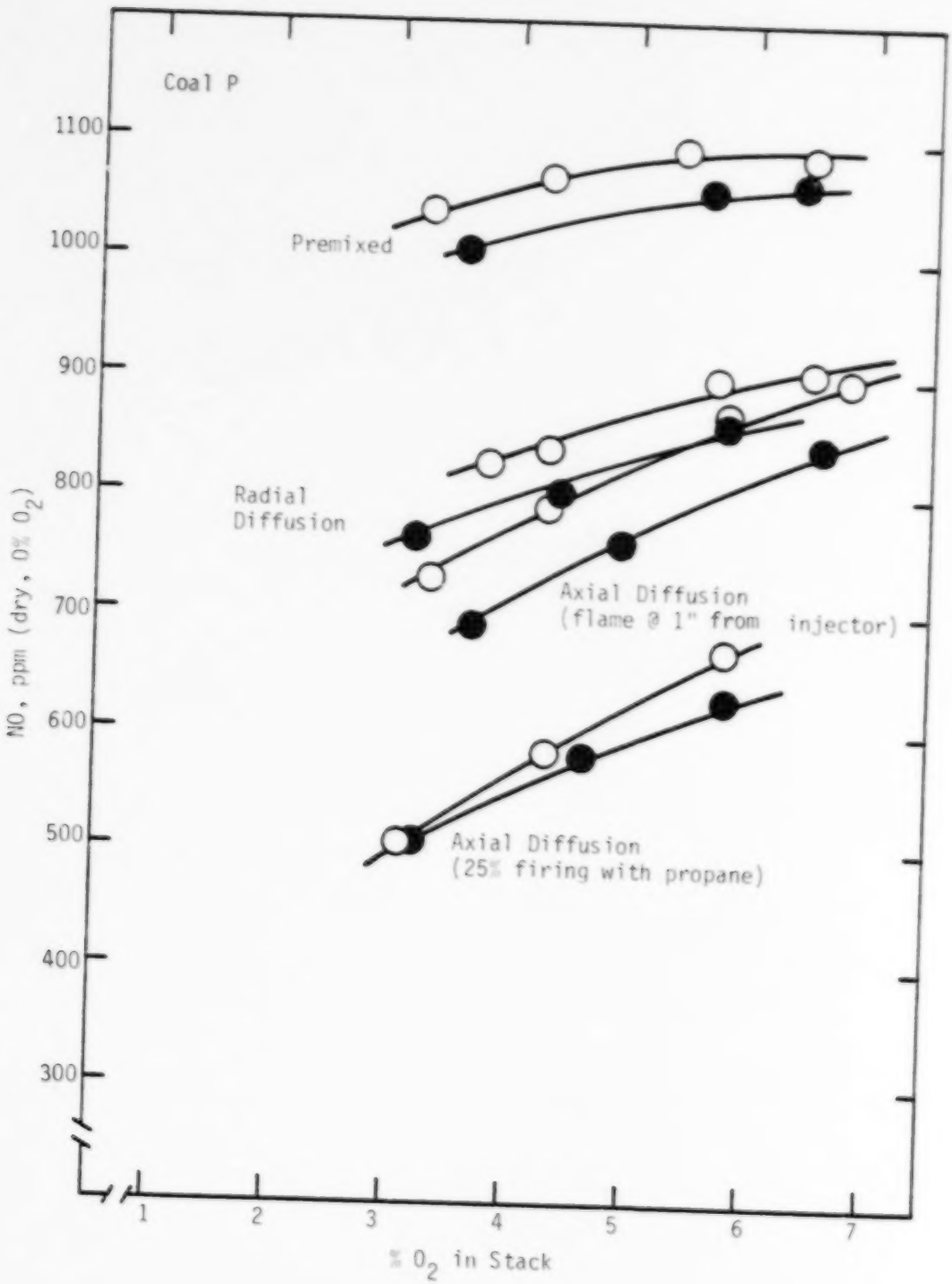

Coal K
1200
1100
1000
900
800
700
600
500
400
Premixed
Radial
Diffusion
Axial
Diffusion
NO, ppm (dry, 0% O_2)
1
2
3
4
5
6
7
% O_2 in Stack

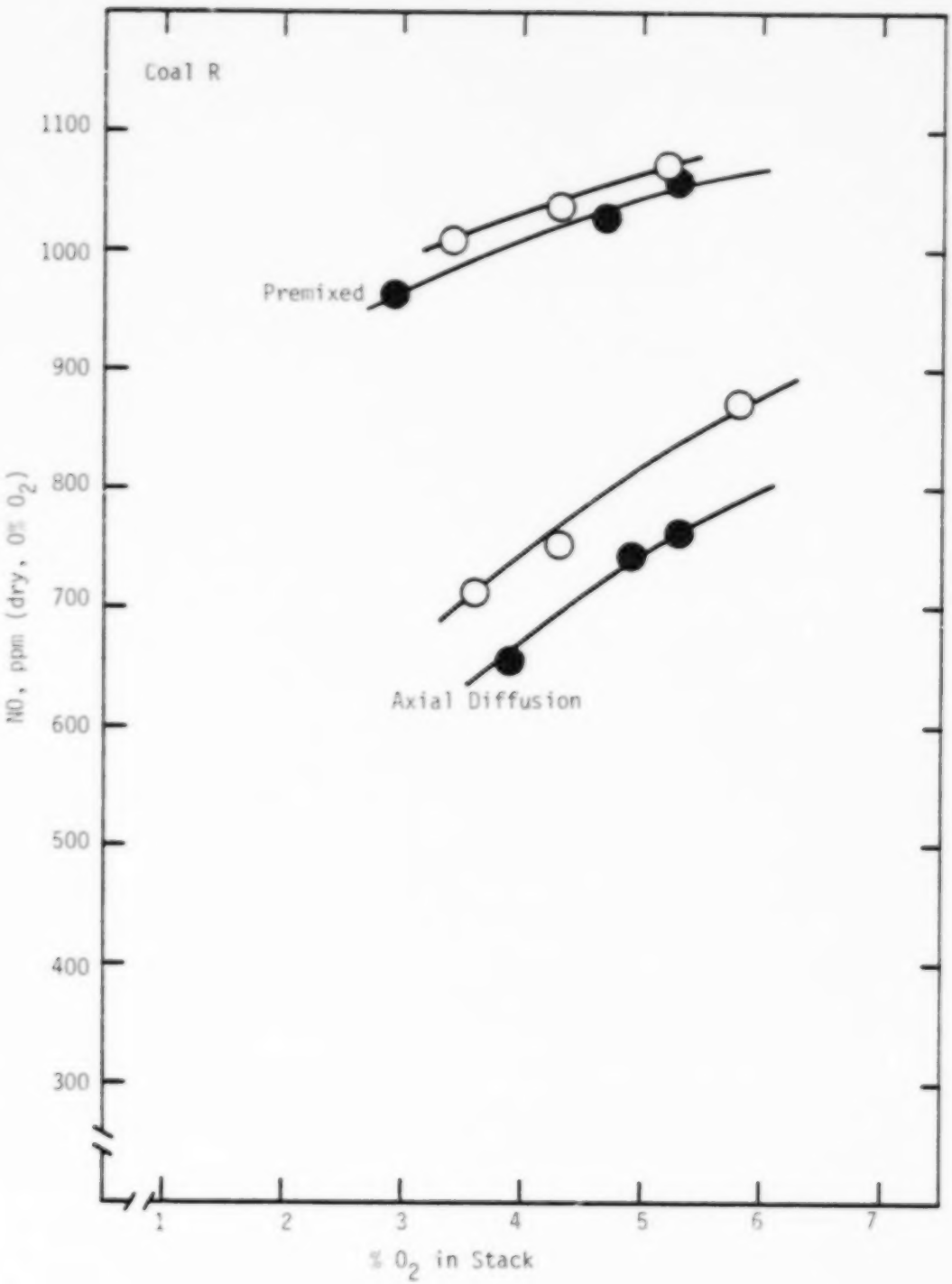

Coal L
1200
1100
1000
900
800
700
600
500
400
Premixed
Radial
Diffusion
Axial
Diffusion
NO, ppm (dry, 0% O_2)
1
2
3
4
5
6
7
% O_2 in Stack

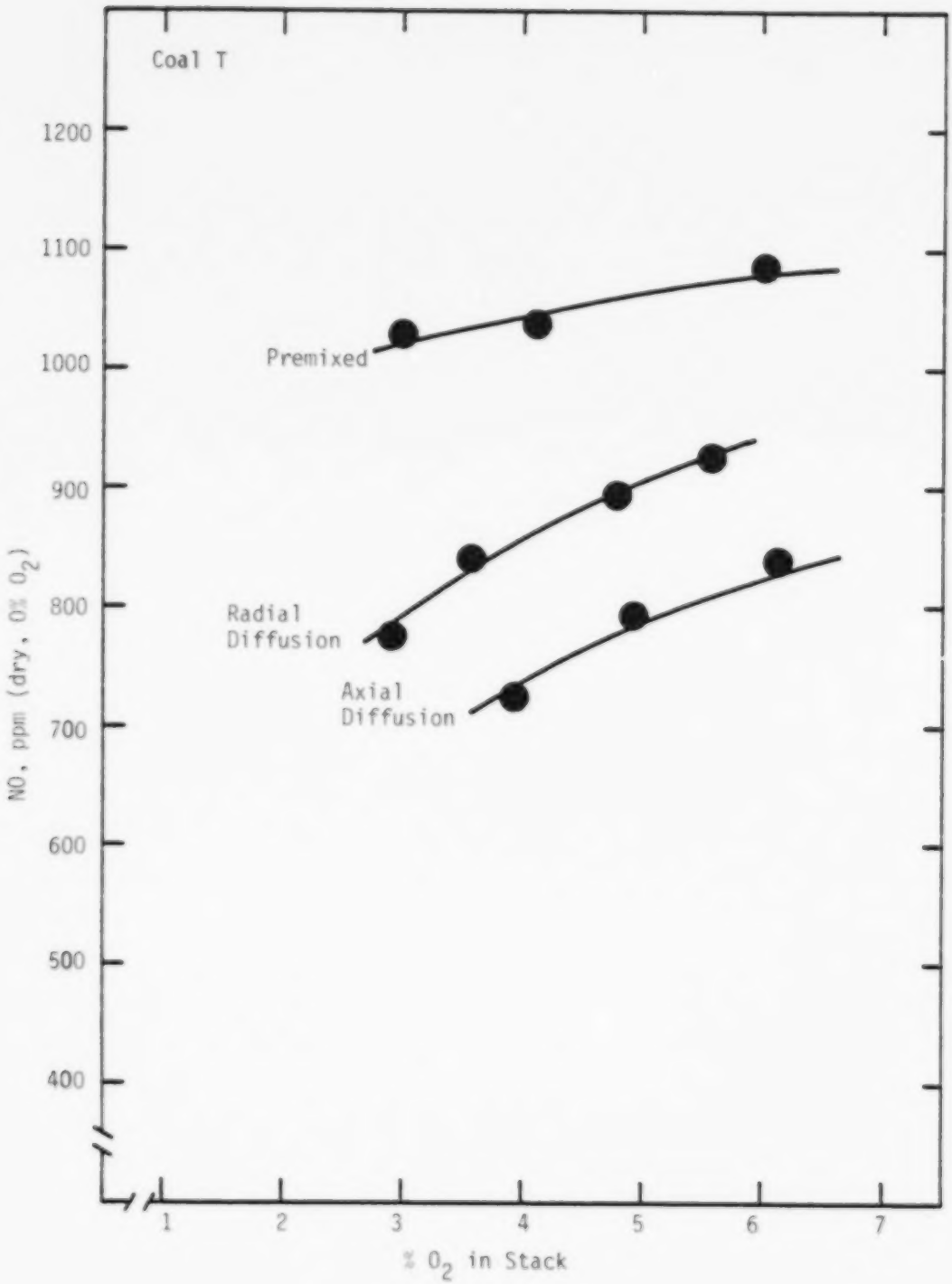

Coal M
1200
1100
1000
900
800
700
600
500
400
NO, ppm (dry, 0% O_2)
Premixed
Radial
Diffusion
Axial
Diffusion
1
2
3
4
5
6
7
% O_2 in Stack

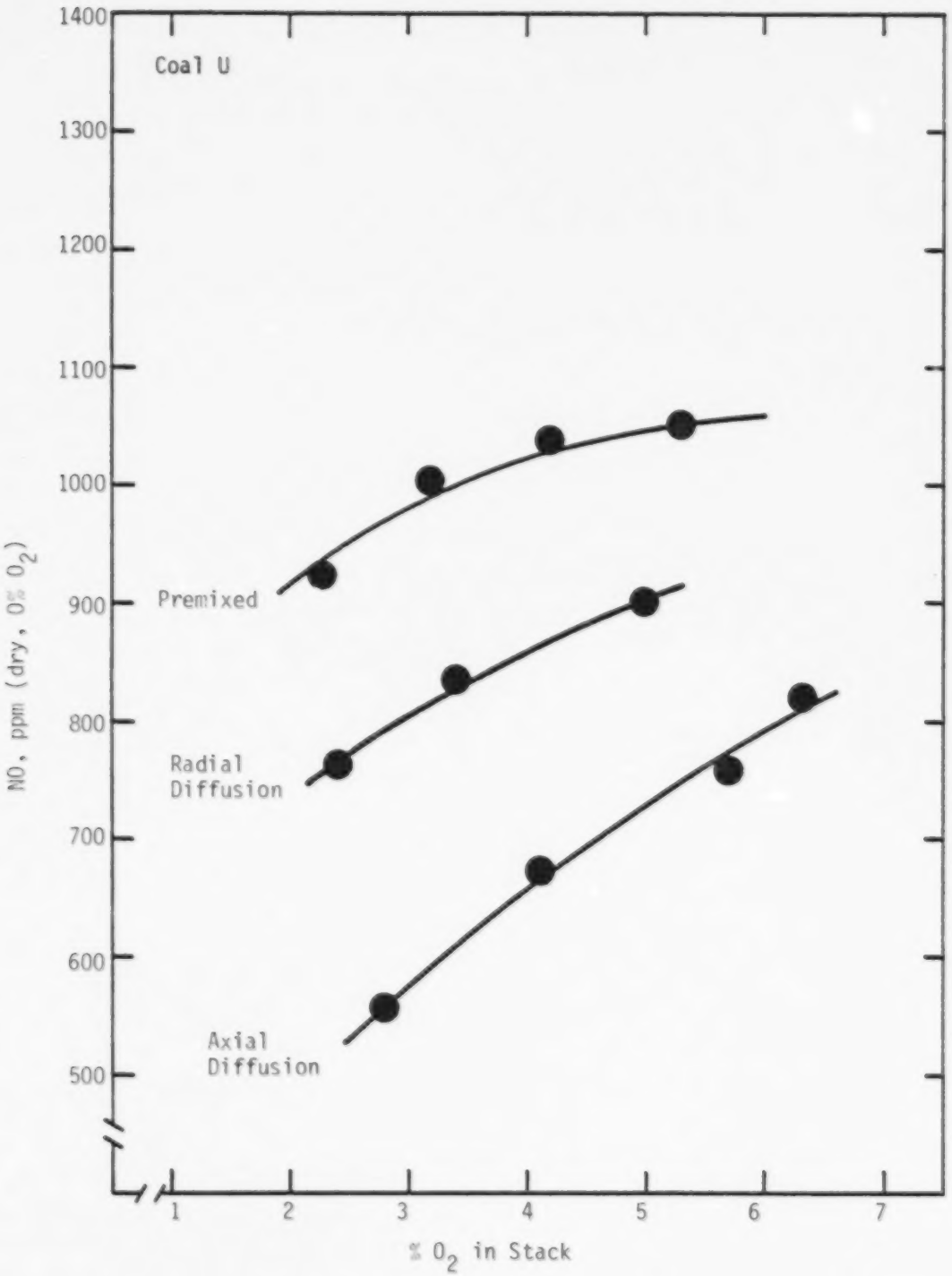

Coal N
Premixed
Radial
Diffusion
Axial
Diffusion
NO, ppm (Dry, 0% O_2)
1400
1300
1200
1100
1000
900
800
700
600
500
400
1
2
3
4
5
6
7
% O_2 in Stack


Coal O
Premixed
Radial
Diffusion
Axial
Diffusion
NO, ppm (dry, 0% O_2)
% O_2 in Stack
1400
1300
1200
1100
1000
900
800
700
600
500
1
2
3
4
5
6
7


Coal P
1100
1000
900
800
700
600
500
400
300
Premixed
Radial
Diffusion
Axial Diffusion
(flame @ 1" from injector)
Axial Diffusion
(25% firing with propane)
NO, ppm (dry, 0% O_2)
1
2
3
4
5
6
7
% O_2 in Stack


Coal R
1100
1000
900
800
700
600
500
400
300
Premixed
Axial Diffusion
NO, ppm (dry, 0% O_2)
1
2
3
4
5
6
7
% O_2 in Stack

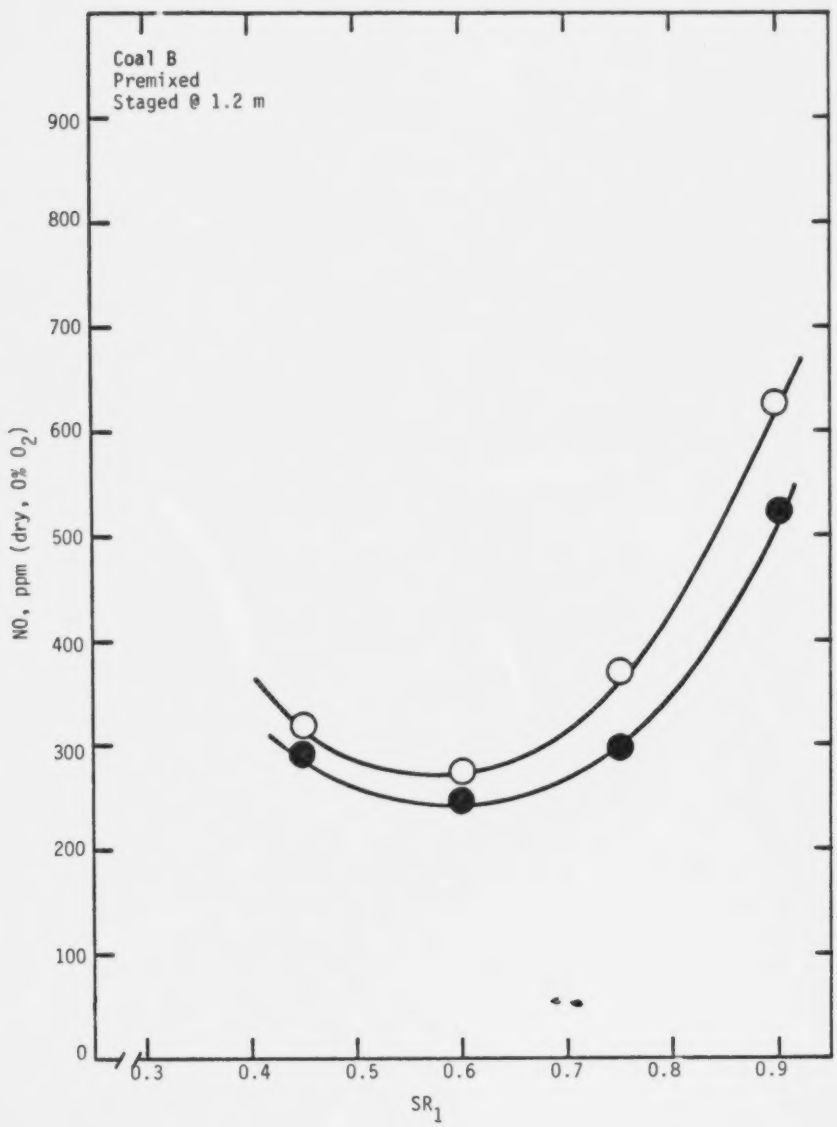

Coal T
1200
1100
1000
900
800
700
600
500
400
NO, ppm (dry, 0% O_2)
Premixed
Radial
Diffusion
Axial
Diffusion
1
2
3
4
5
6
7
% O_2 in Stack

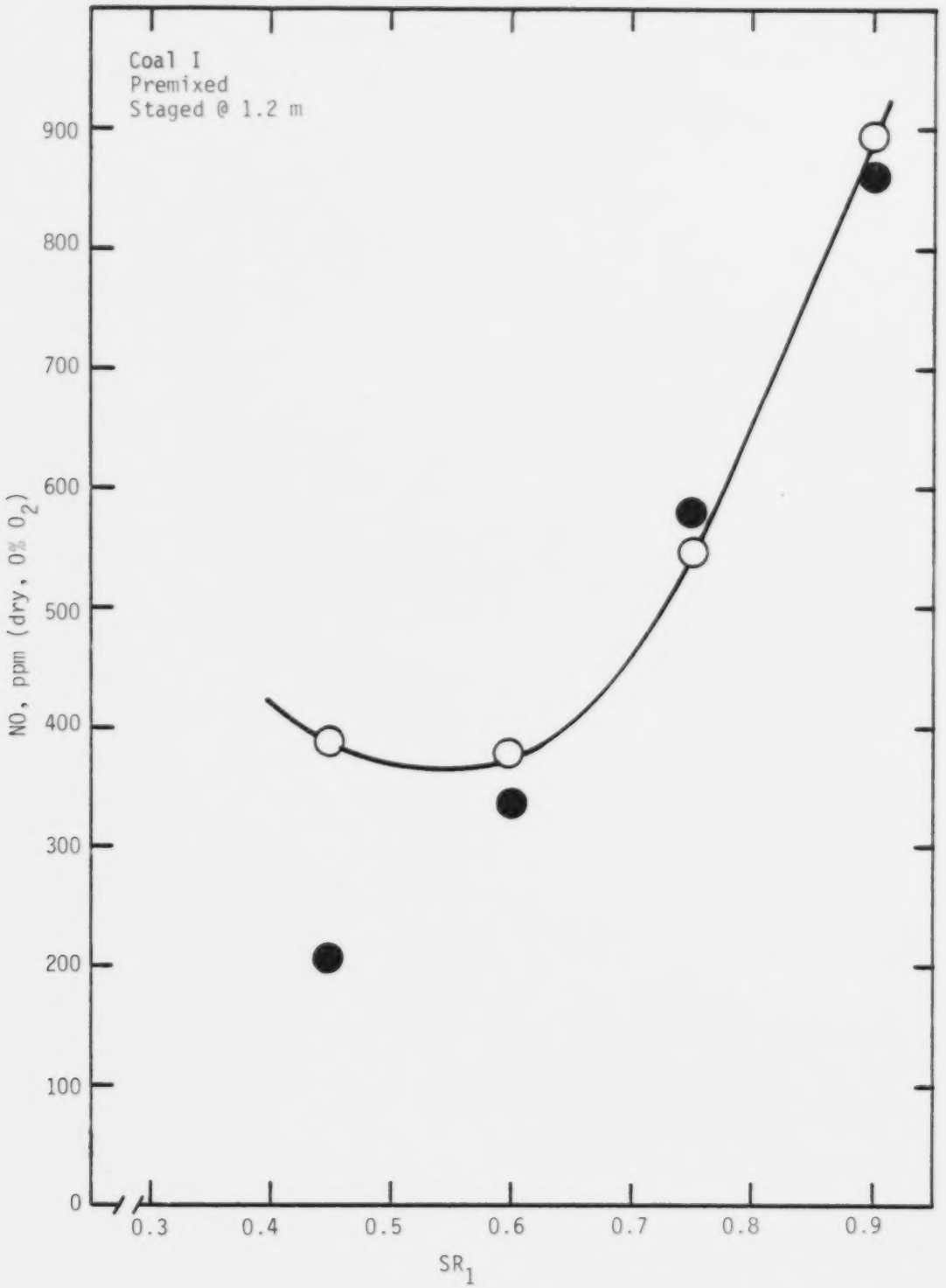

Coal U
1400
1300
1200
1100
1000
900
800
700
600
500
Premixed
Radial
Diffusion
Axial
Diffusion
NO, ppm (dry, 0% O_2)
1
2
3
4
5
6
7
% O_2 in Stack

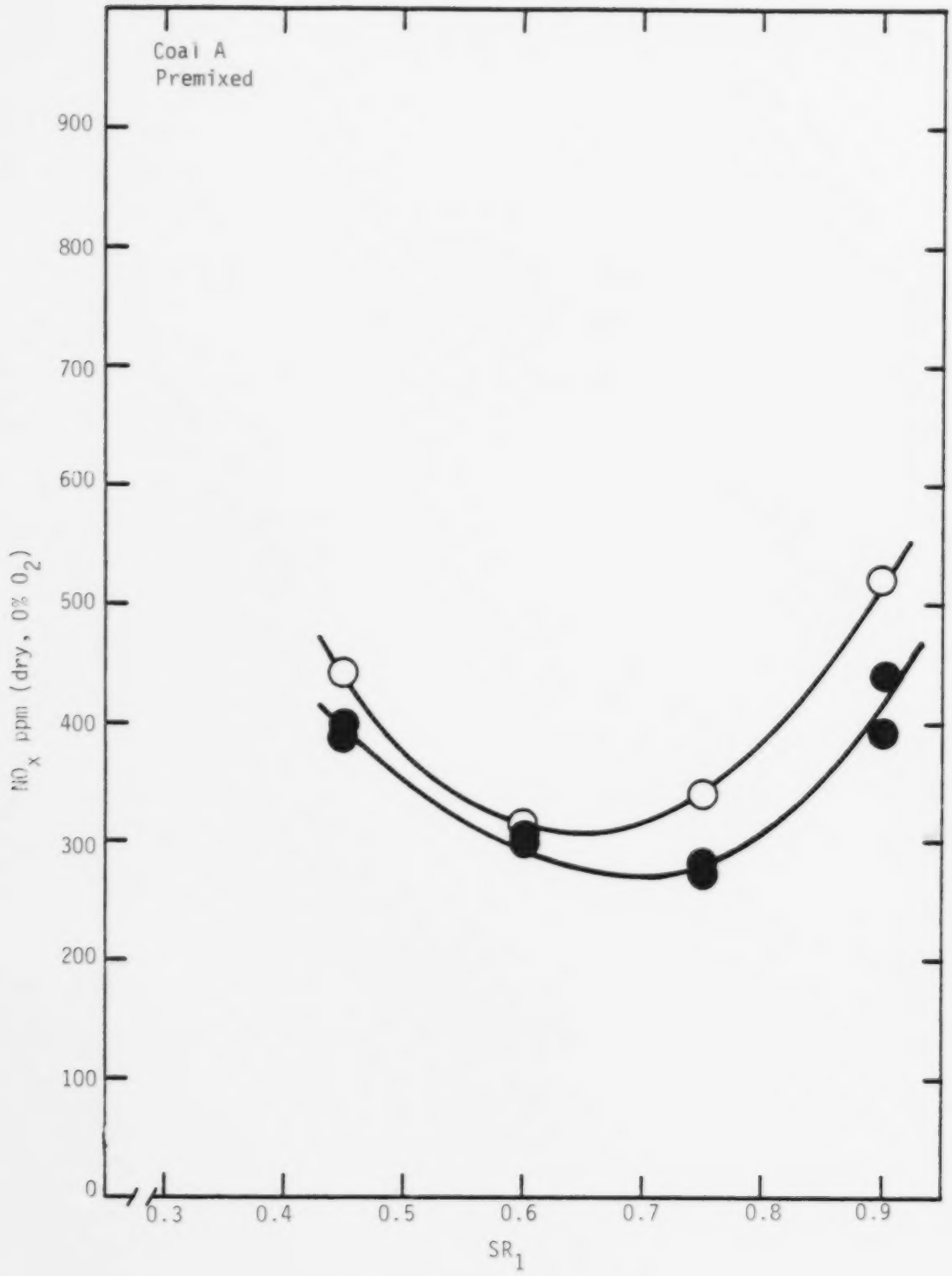
APPENDIX B

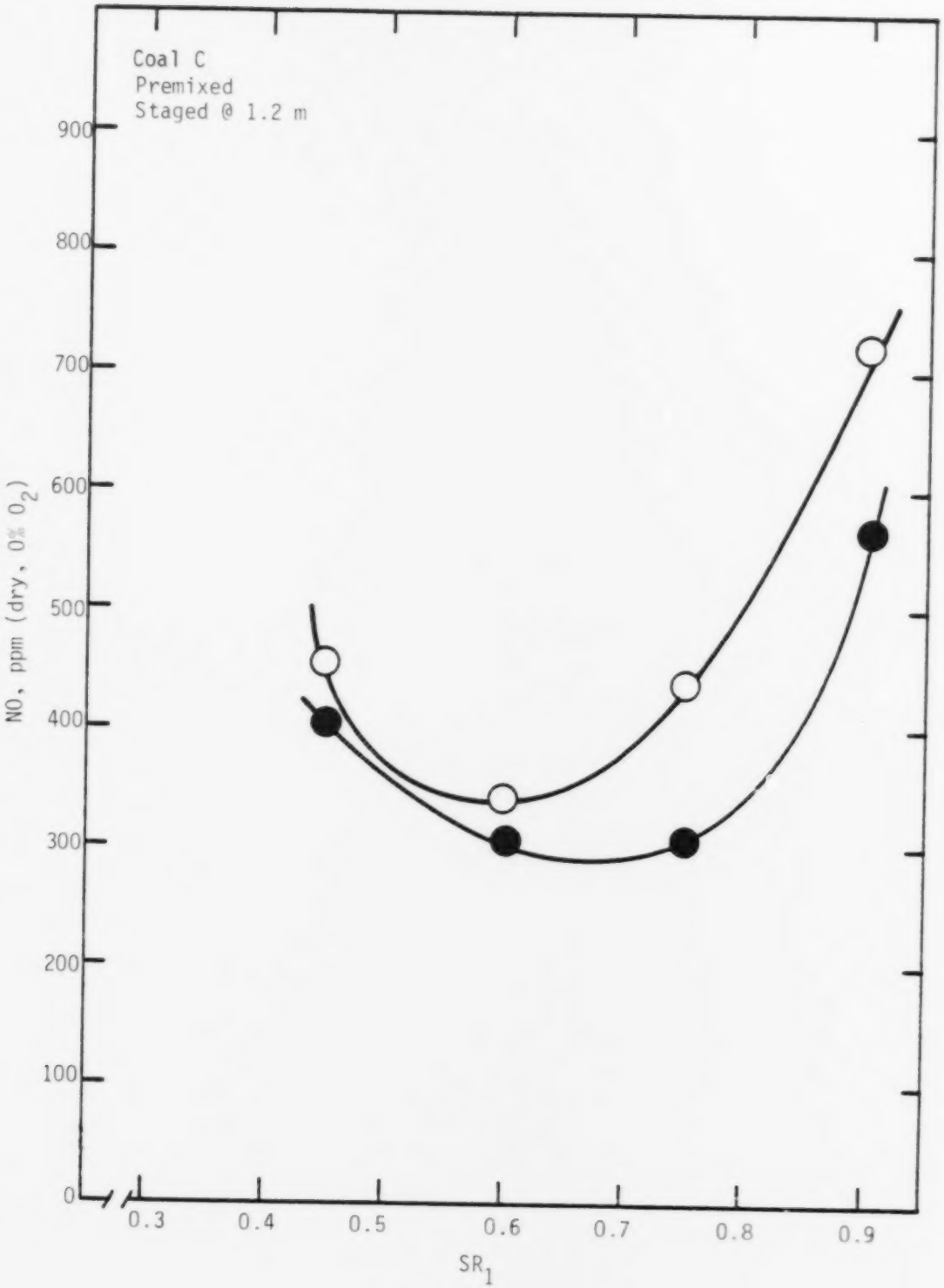
Exhaust NO Emissions as a Function
of First-Stage Stoichiometry

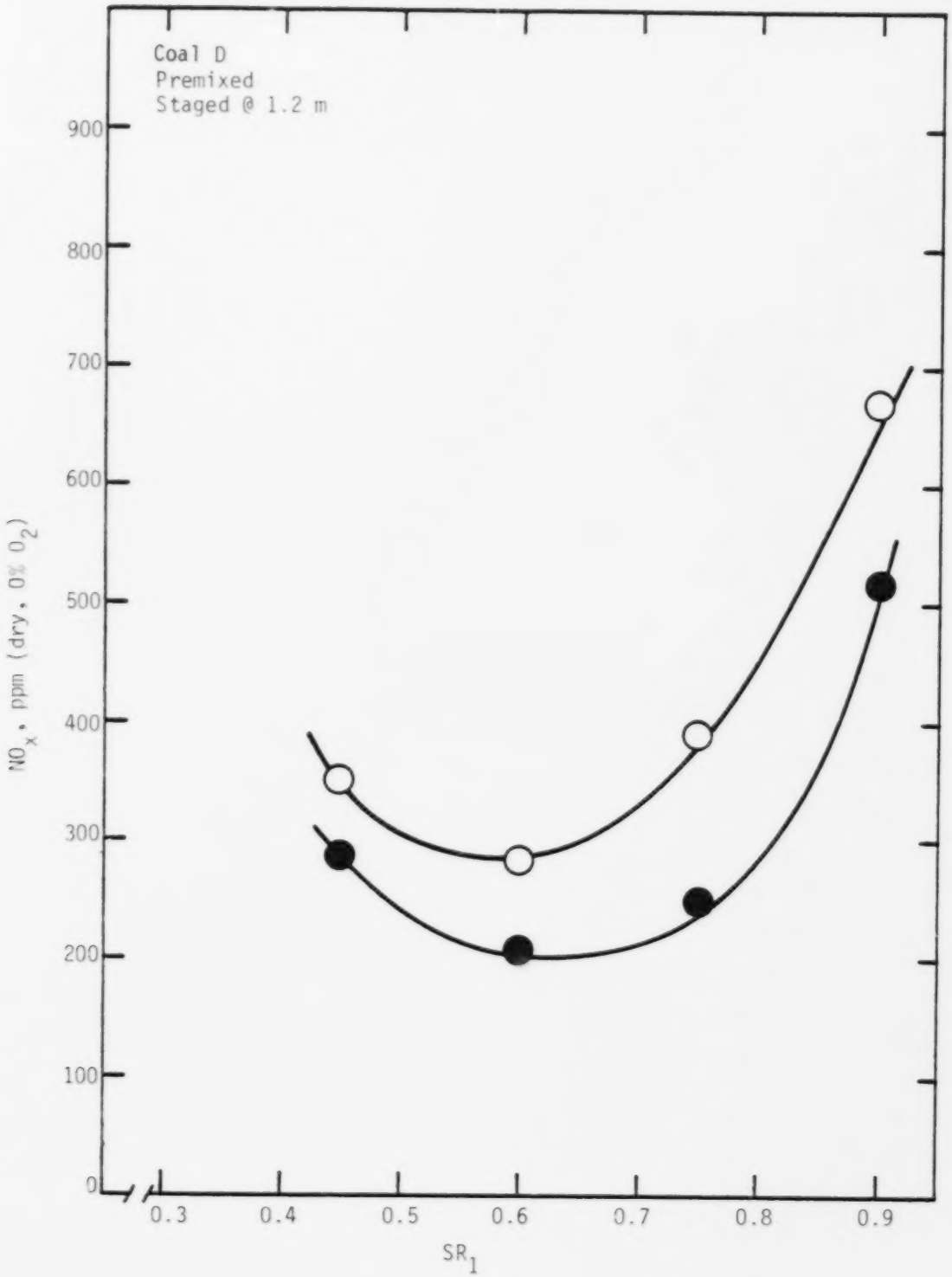
(Open Symbols: Normal
Solid Symbols: First Stage Cooling)

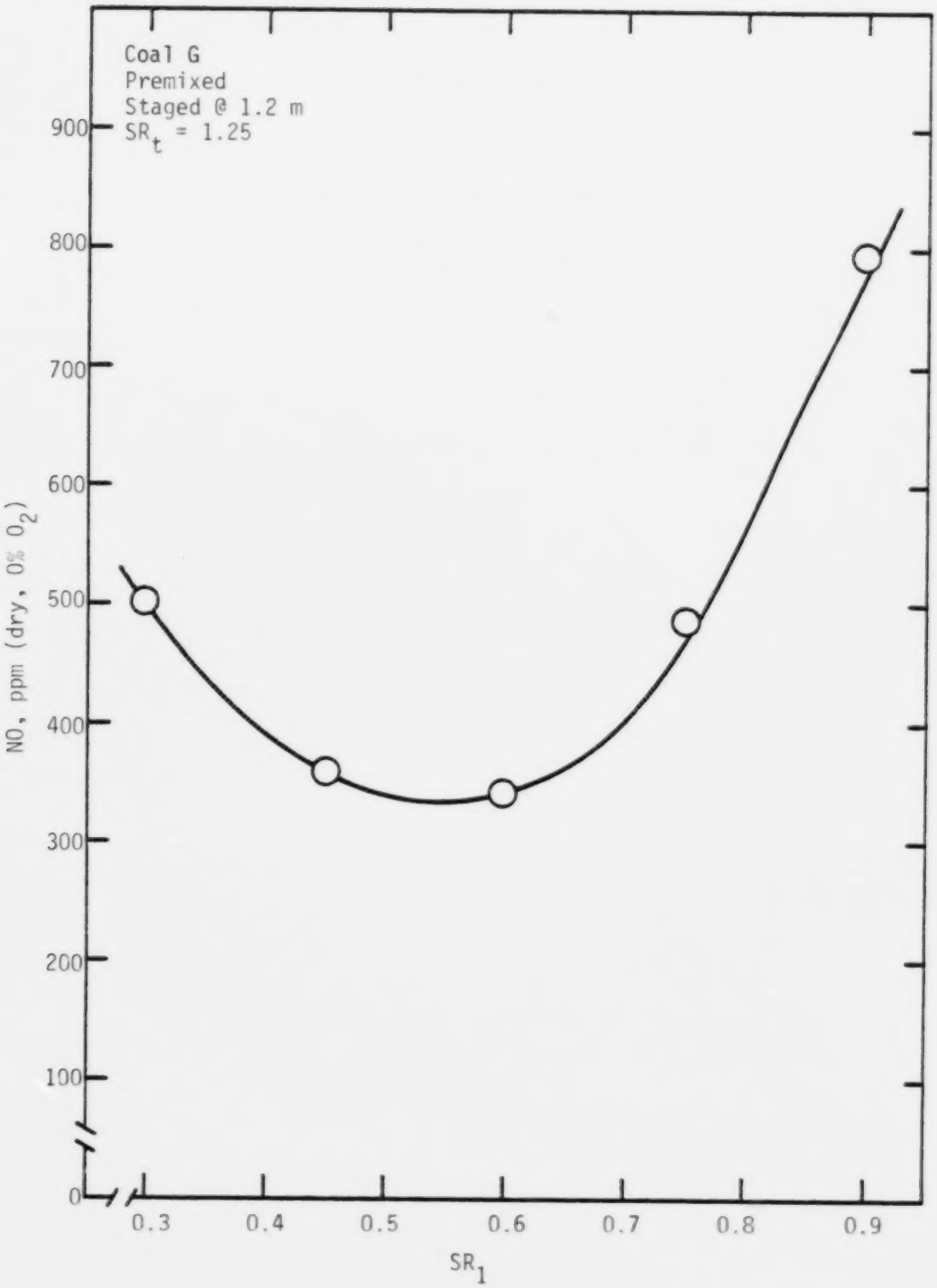


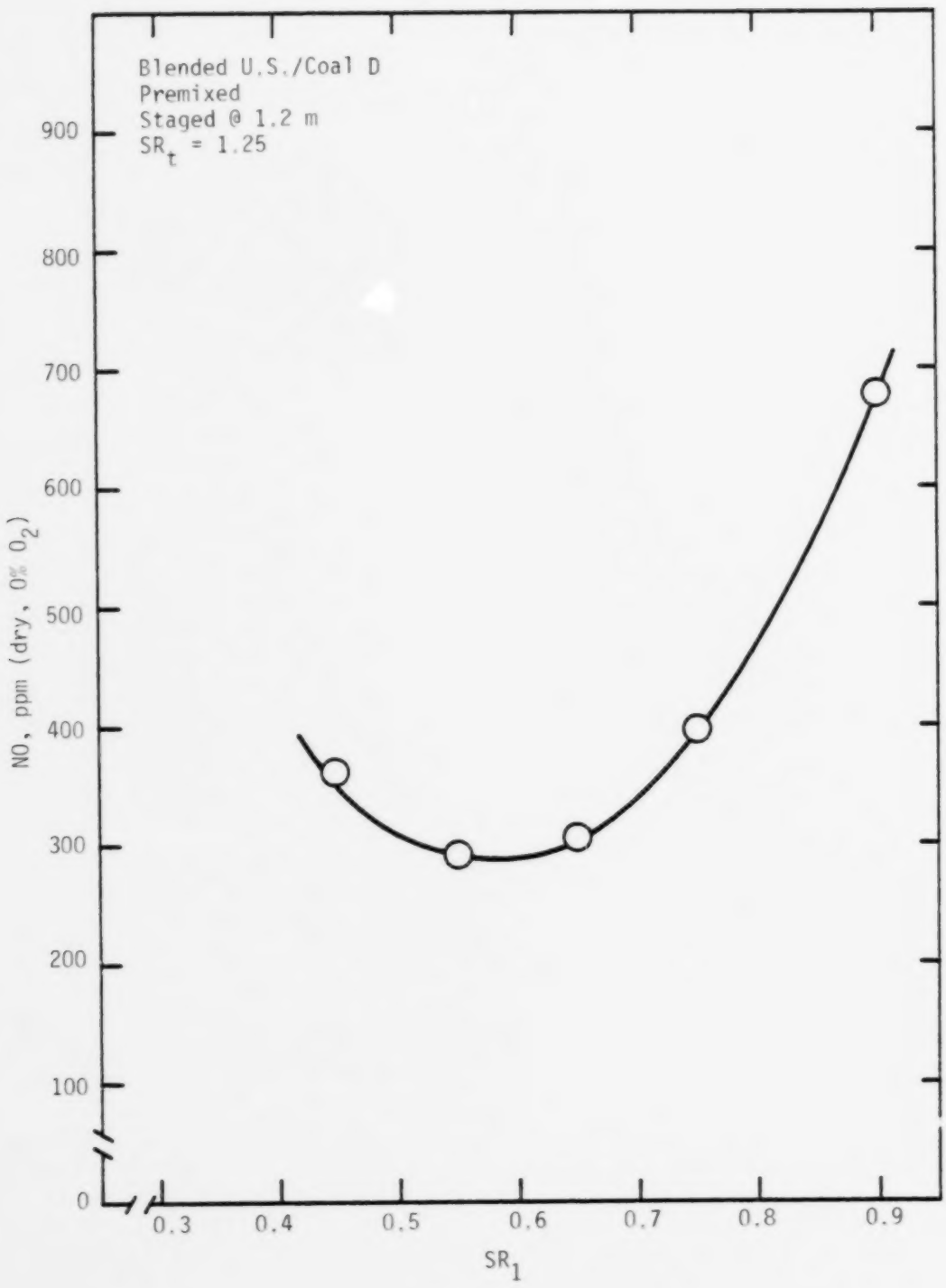

Coal I
Premixed
Staged @ 1.2 m
NO, ppm (dry, 0% O_2)
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1

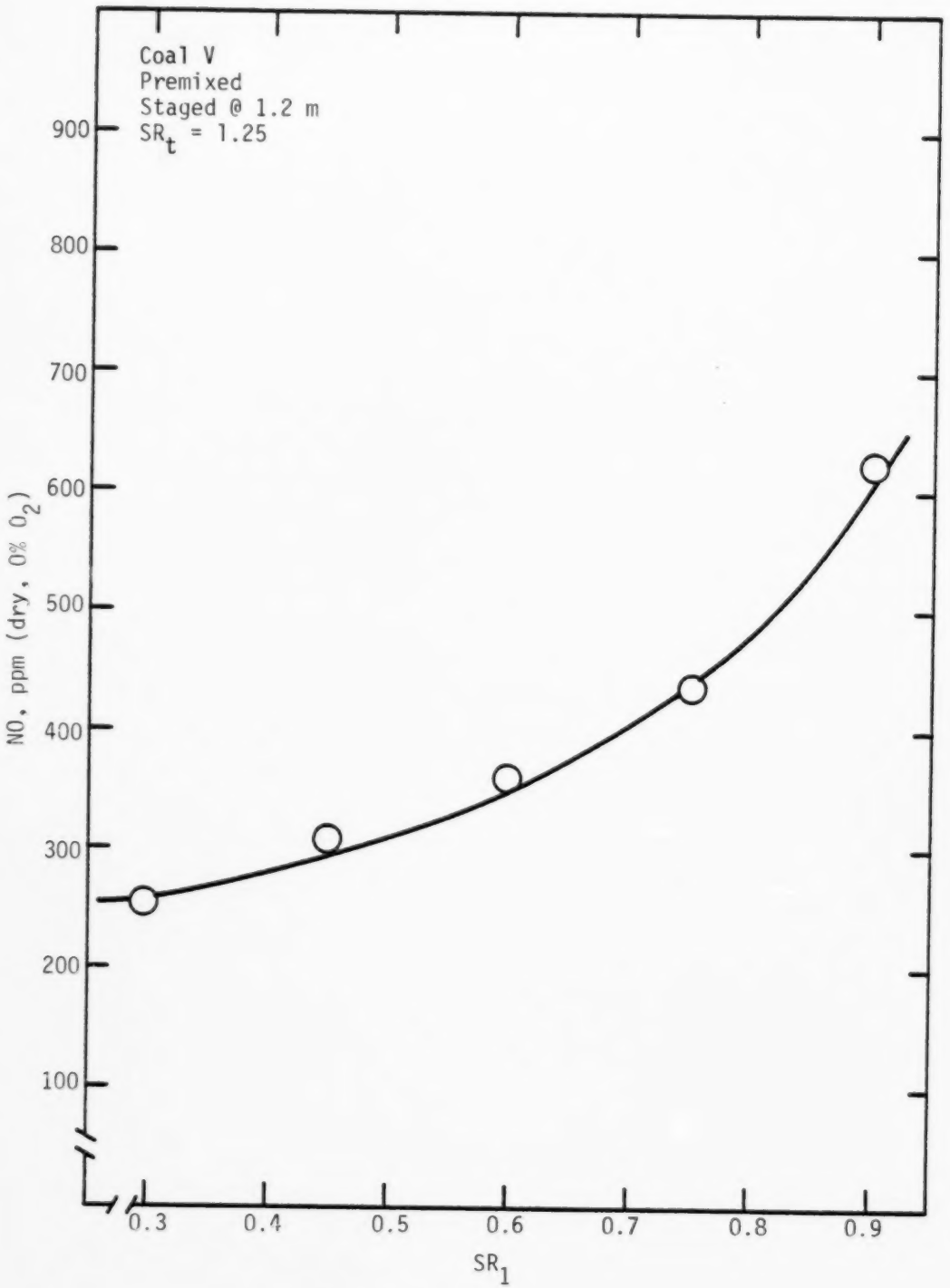

Coal A
Premixed
900
800
700
600
500
400
300
200
100
0
NO_x ppm (dry, 0% O_2)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1

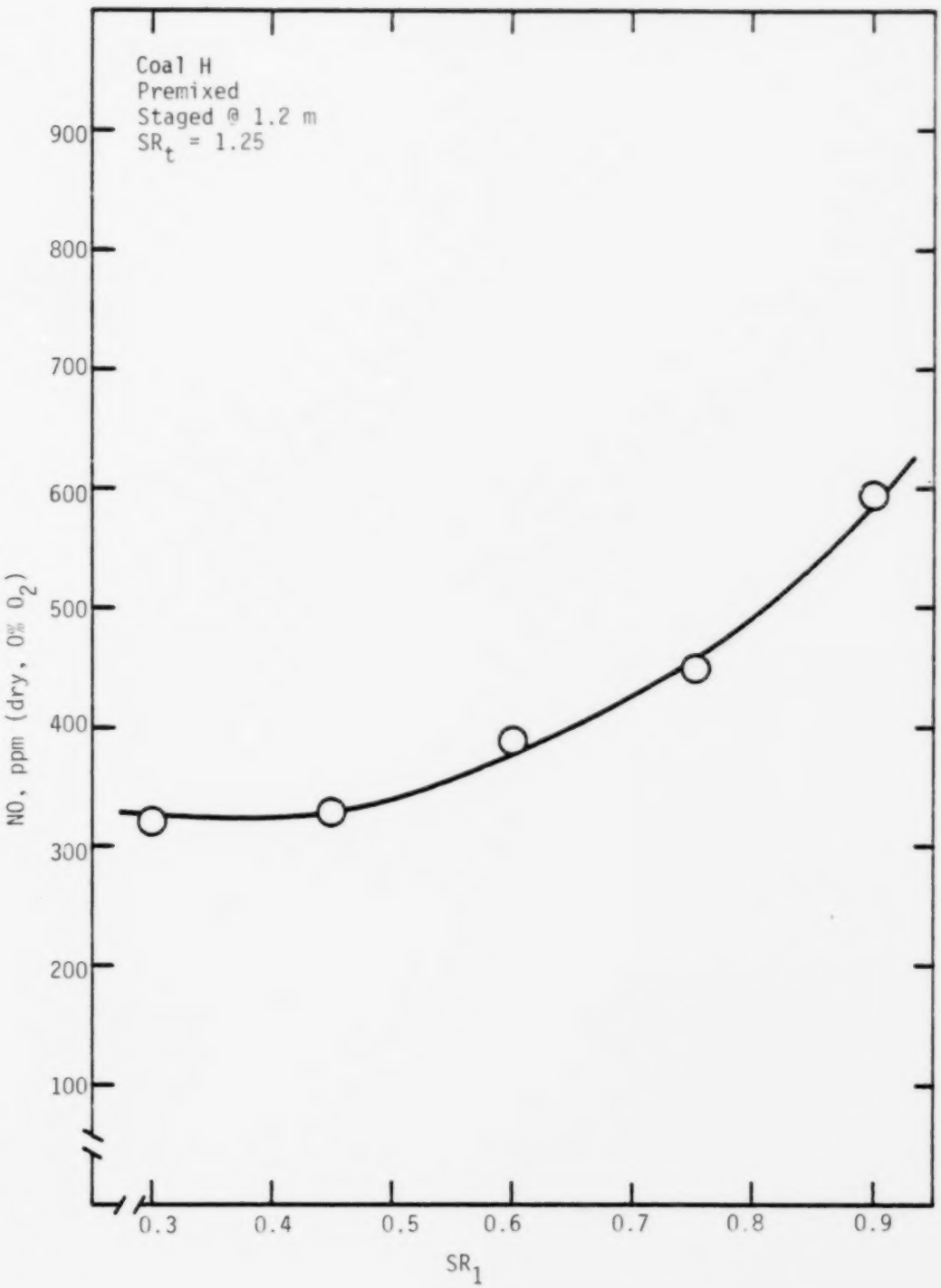

Coal C
Premixed
Staged @ 1.2 m
NO, ppm (dry, 0% O_2)
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1

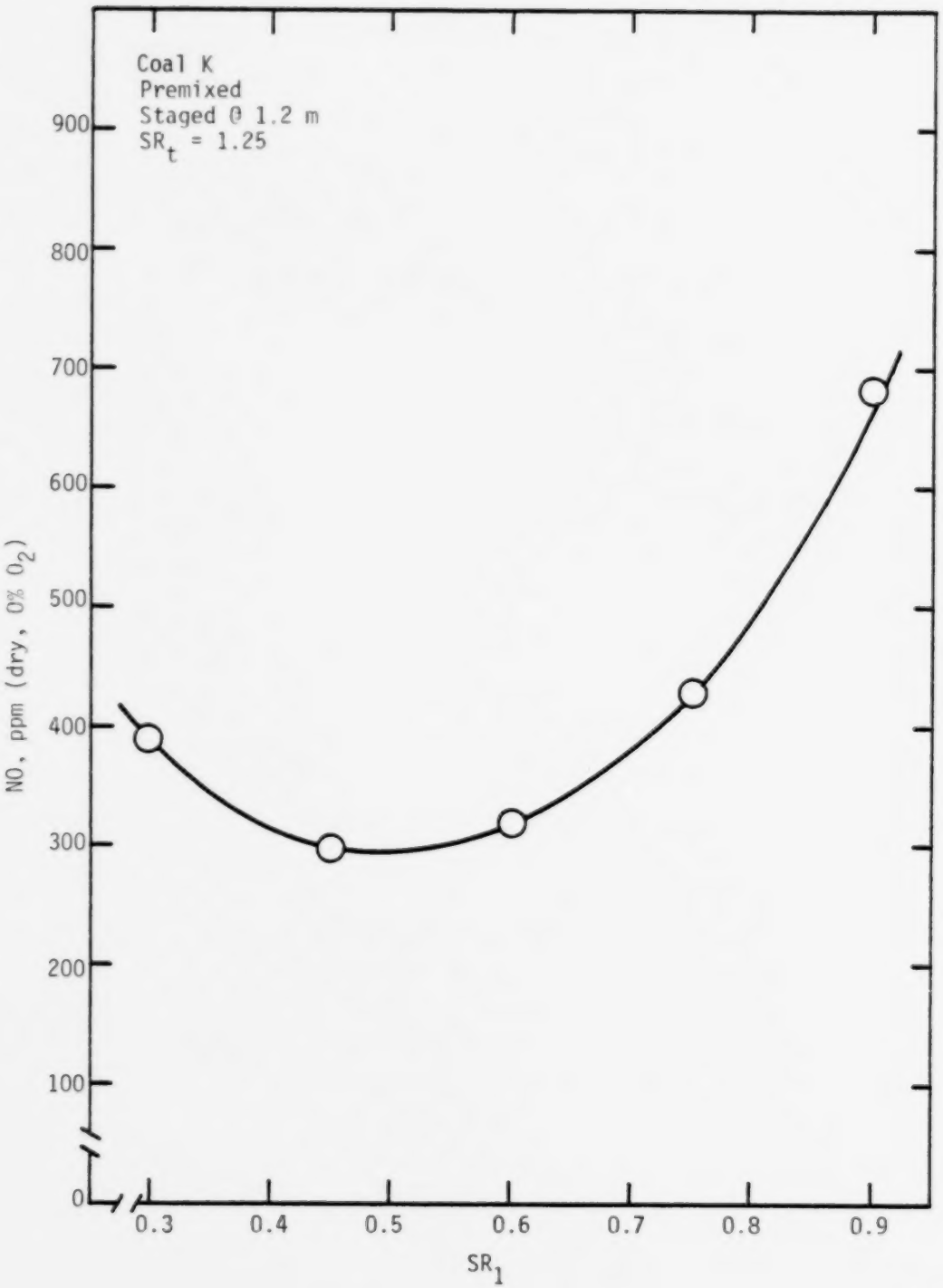

Coal D
Premixed
Staged @ 1.2 m
900
800
700
600
500
400
300
200
100
0
NO_x, ppm (dry, 0% O_2)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1

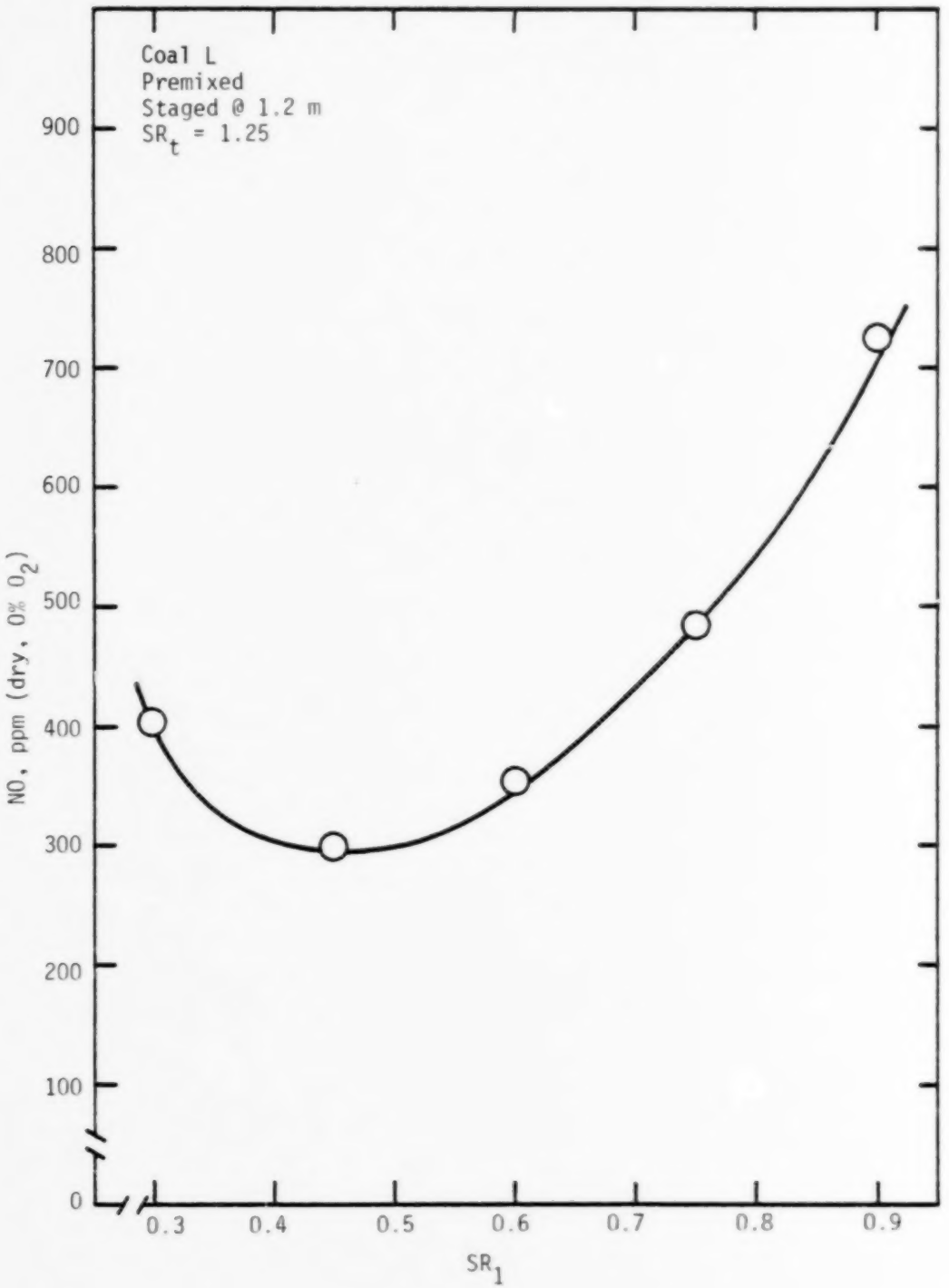

Coal G
Premixed
Staged @ 1.2 m
SR$_t$ = 1.25
NO, ppm (dry, 0% O$_2$)
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR$_1$

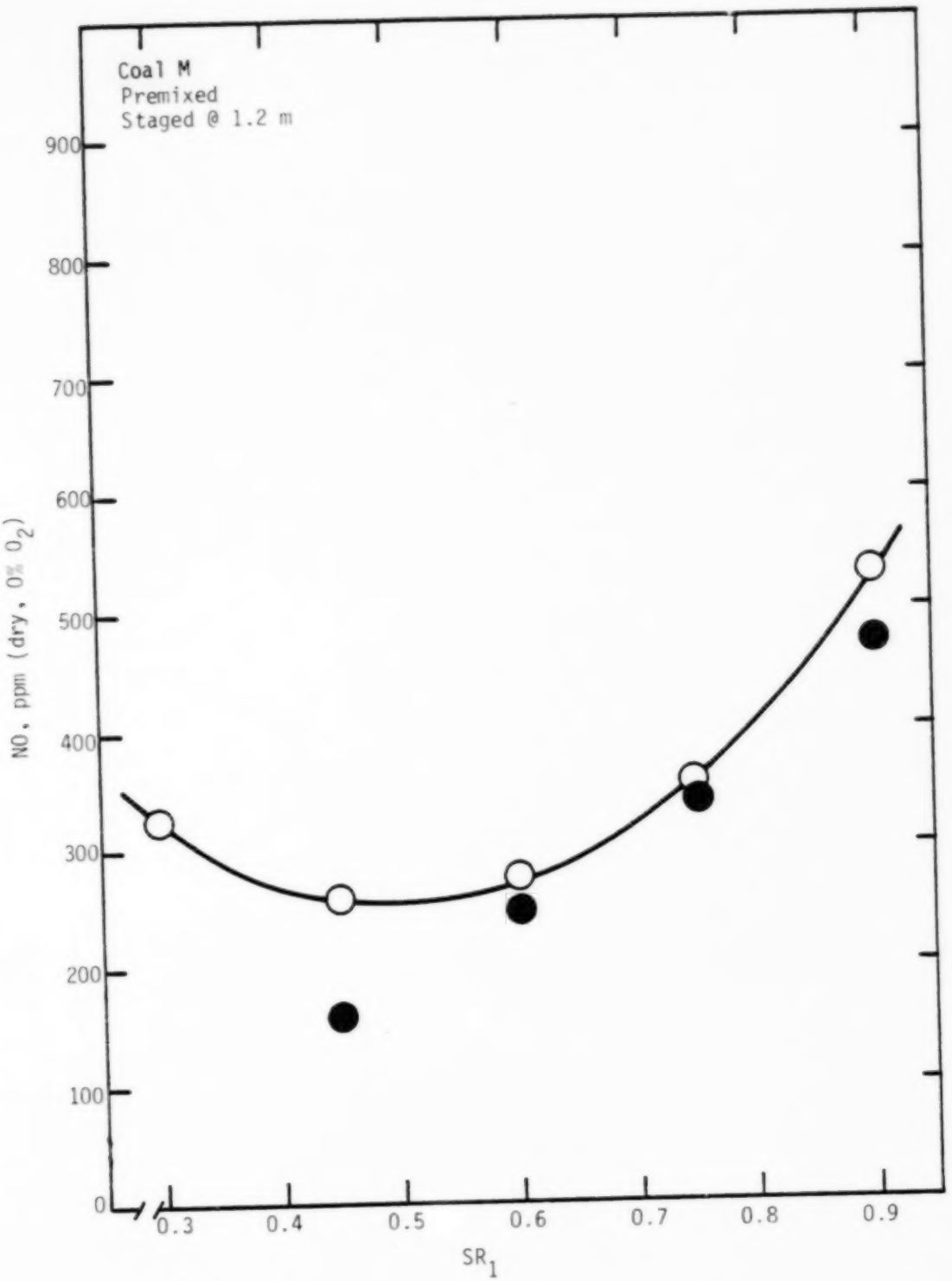

Blended U.S./Coal D
Premixed
Staged @ 1.2 m
SR_t = 1.25
NO, ppm (dry, 0% O_2)
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1

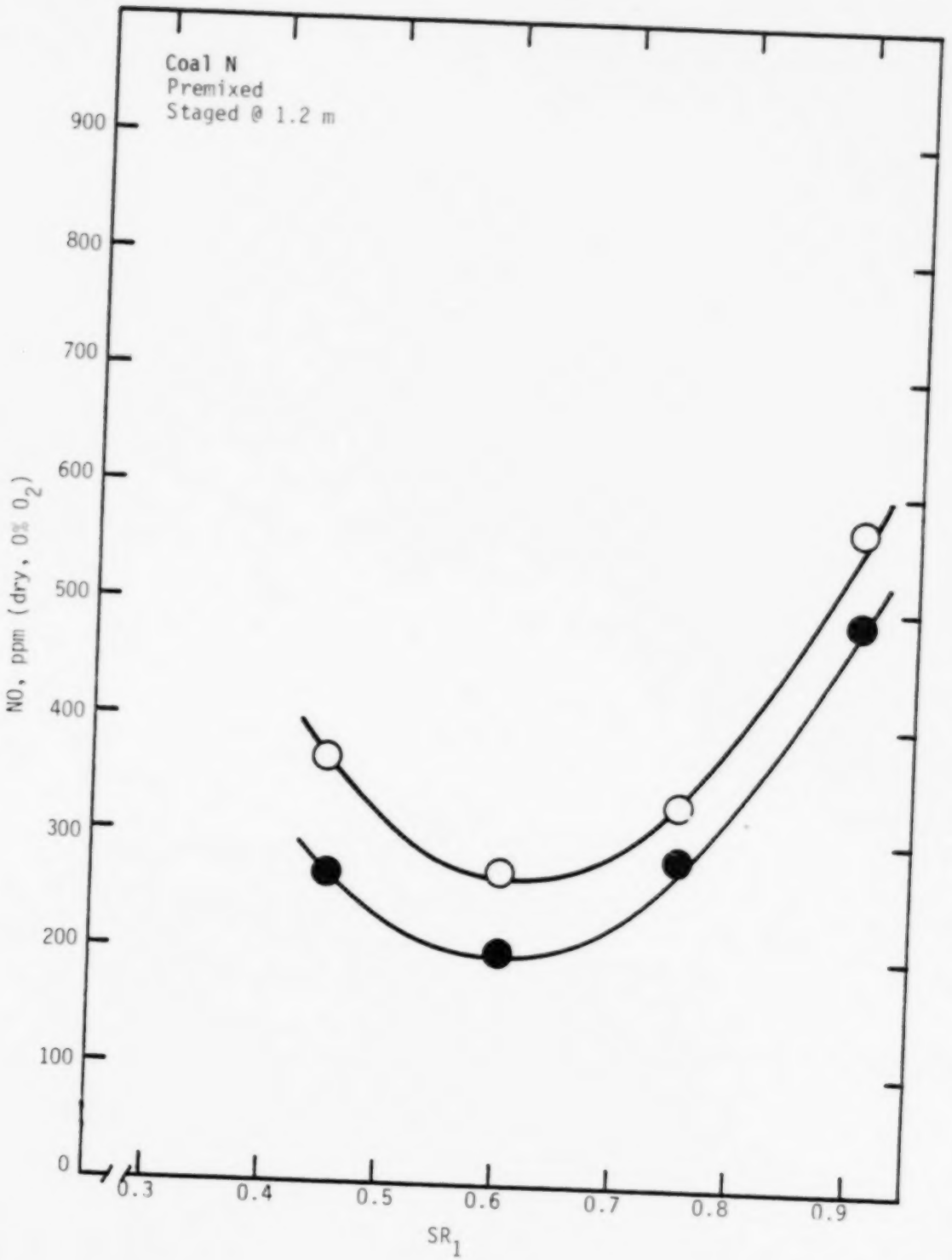

Coal V
Premixed
Staged @ 1.2 m
SR_t = 1.25
NO, ppm (dry, 0% O_2)
900
800
700
600
500
400
300
200
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1

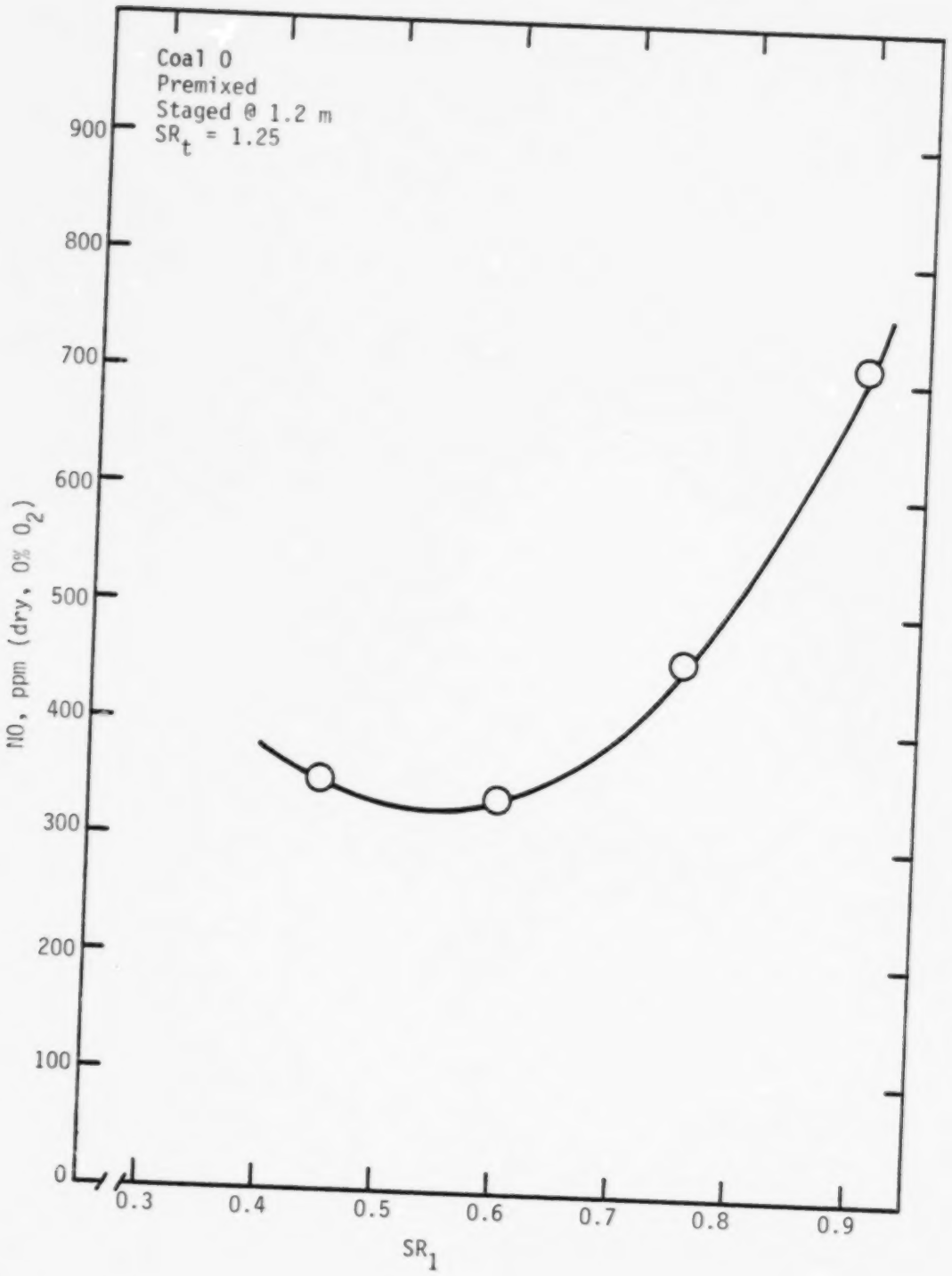

Coal H
Premixed
Staged @ 1.2 m
SR$_t$ = 1.25
NO, ppm (dry, 0% O$_2$)
900
800
700
600
500
400
300
200
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR$_1$

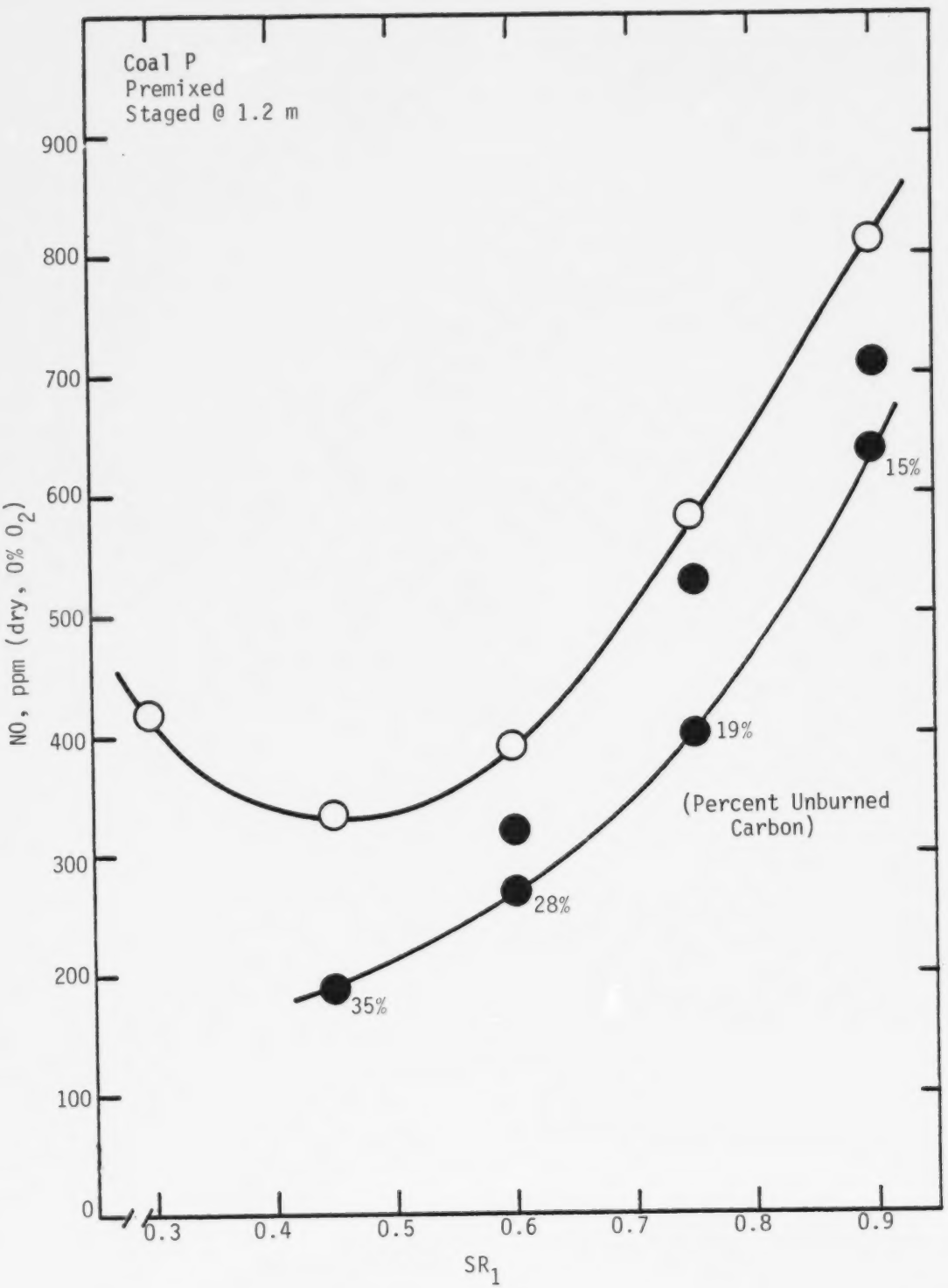

Coal K
Premixed
Staged @ 1.2 m
SR$_t$ = 1.25
NO, ppm (dry, 0% O$_2$)
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR$_1$

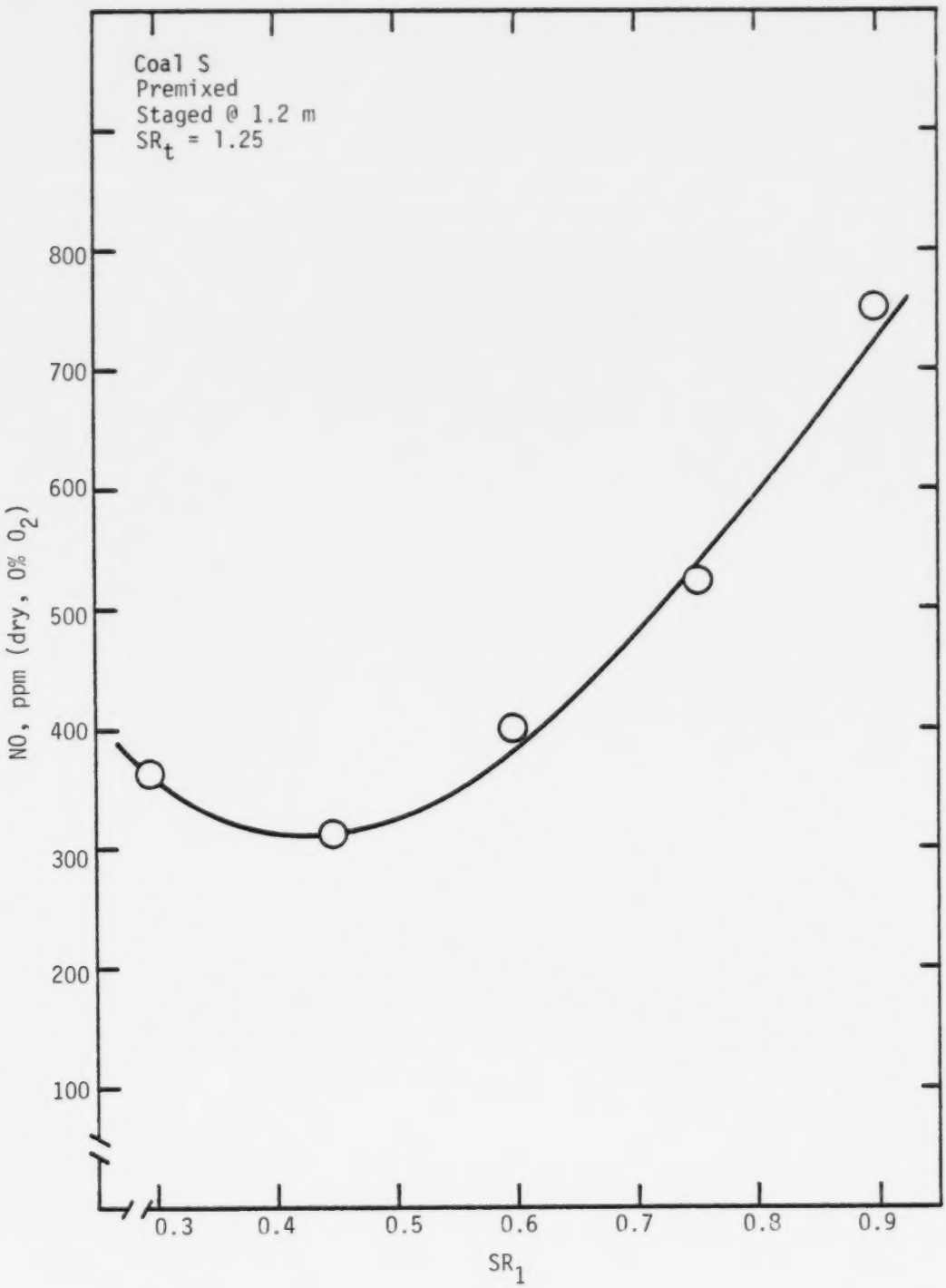

Coal L
Premixed
Staged @ 1.2 m
SR$_t$ = 1.25
NO, ppm (dry, 0% O$_2$)
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR$_1$

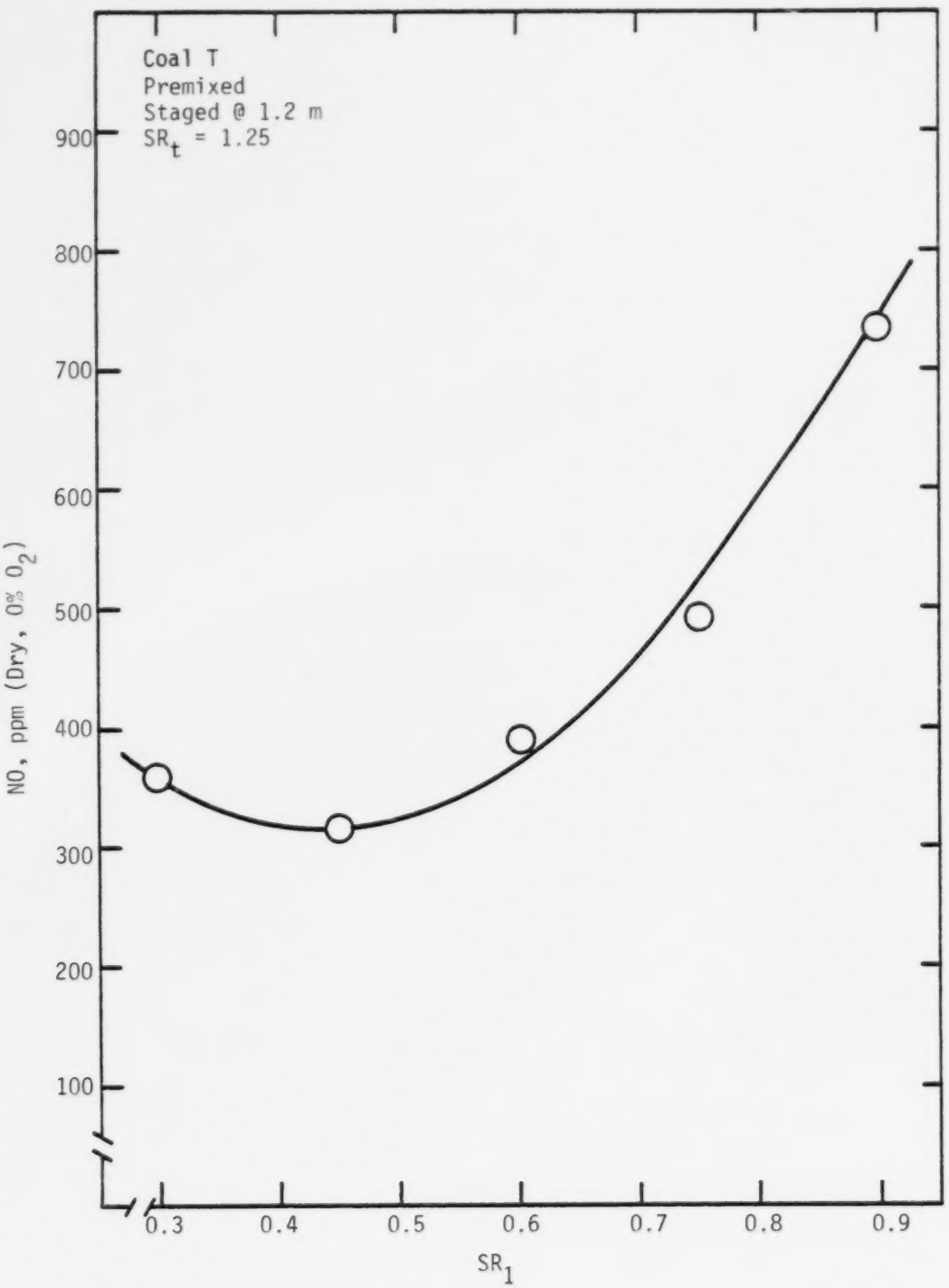

Coal M
Premixed
Staged @ 1.2 m
900
800
700
600
500
400
300
200
100
0
NO, ppm (dry, 0% O_2)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1

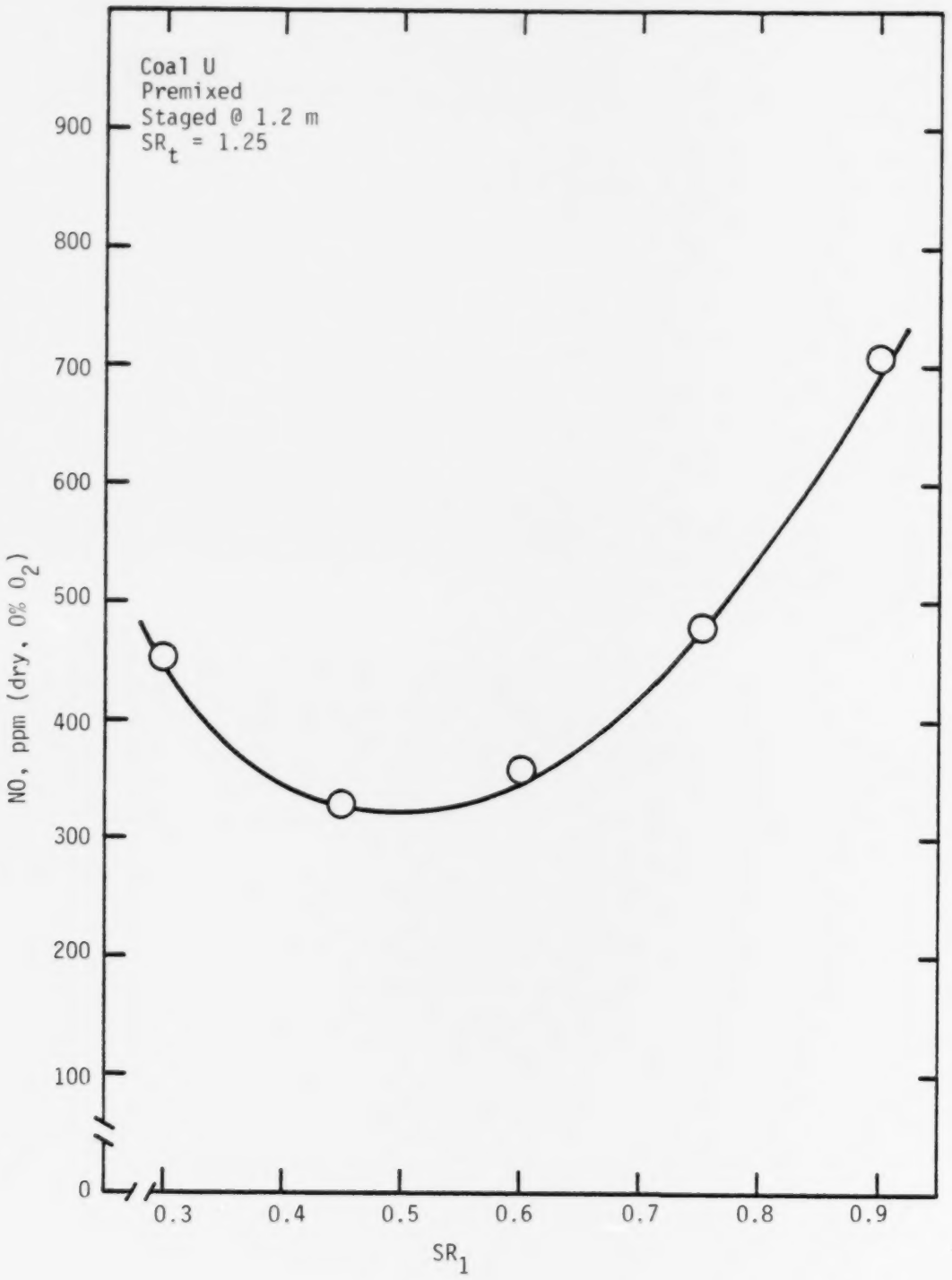

Coal N
Premixed
Staged @ 1.2 m
900
800
700
600
500
400
300
200
100
0
NO, ppm (dry, 0% O_2)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1


Coal 0
Premixed
Staged @ 1.2 m
SR$_t$ = 1.25
NO, ppm (dry, 0% O$_2$)
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR$_1$


Coal P
Premixed
Staged @ 1.2 m
NO, ppm (dry, 0% O_2)
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1
15%
19%
28%
35%
(Percent Unburned Carbon)

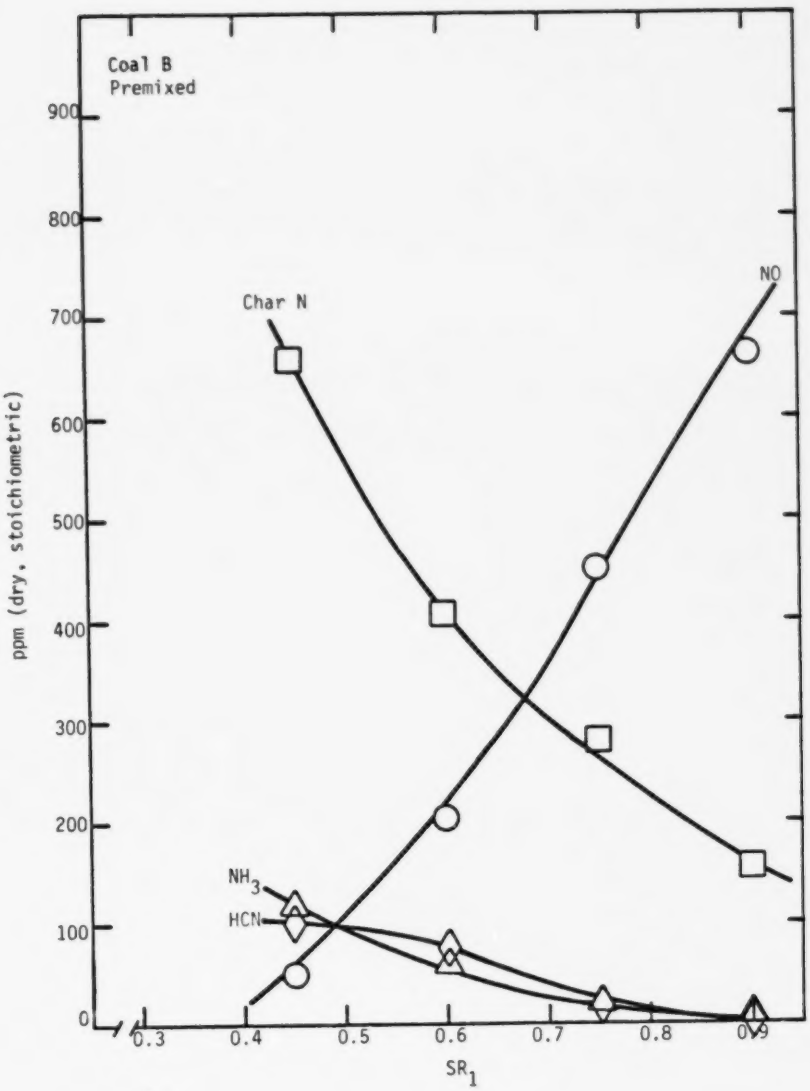

Coal S
Premixed
Staged @ 1.2 m
SR_t = 1.25
NO, ppm (dry, 0% O_2)
800
700
600
500
400
300
200
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1

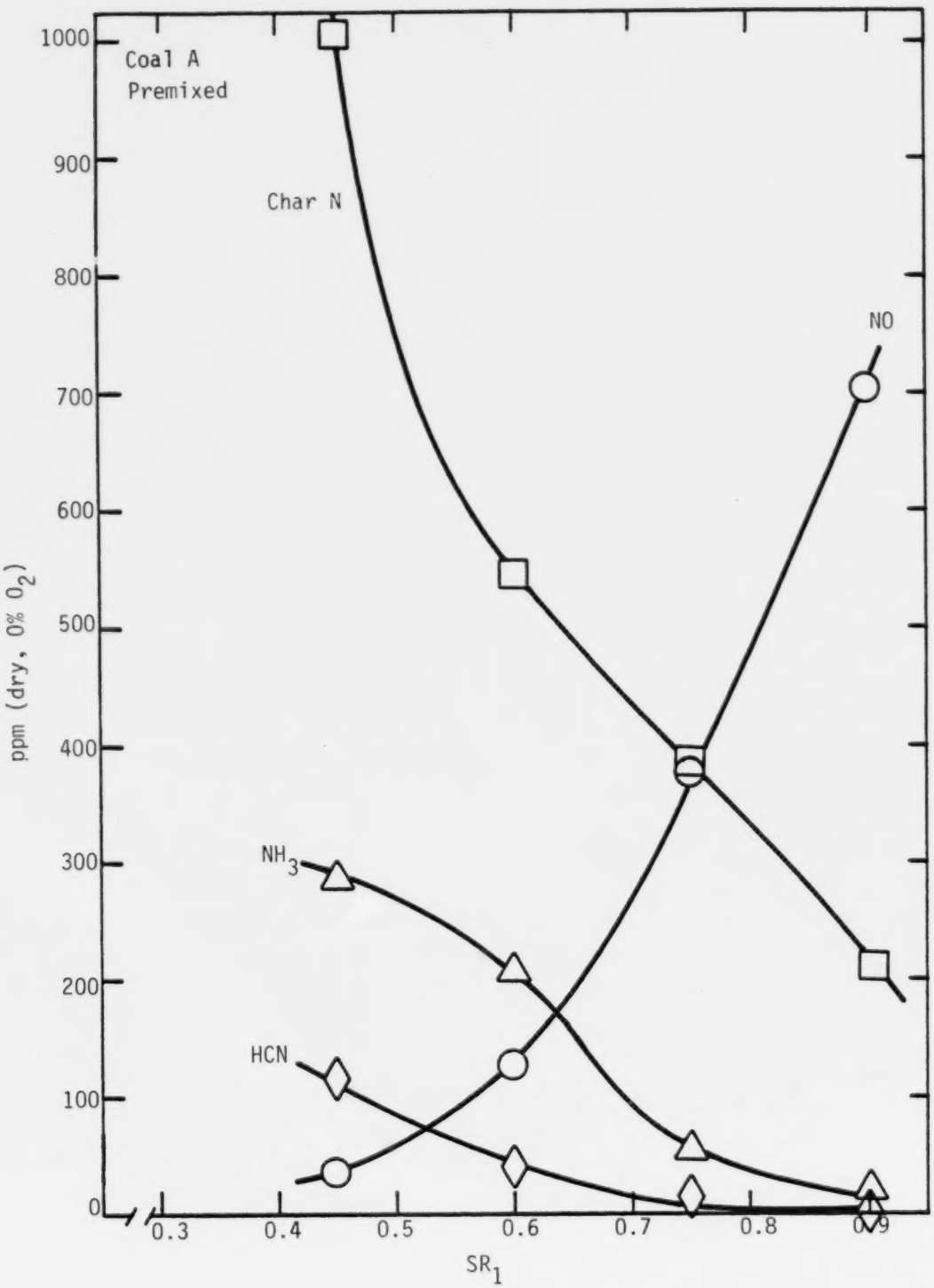

Coal T
Premixed
Staged @ 1.2 m
SR$_t$ = 1.25
NO, ppm (Dry, 0% O$_2$)
900
800
700
600
500
400
300
200
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR$_1$

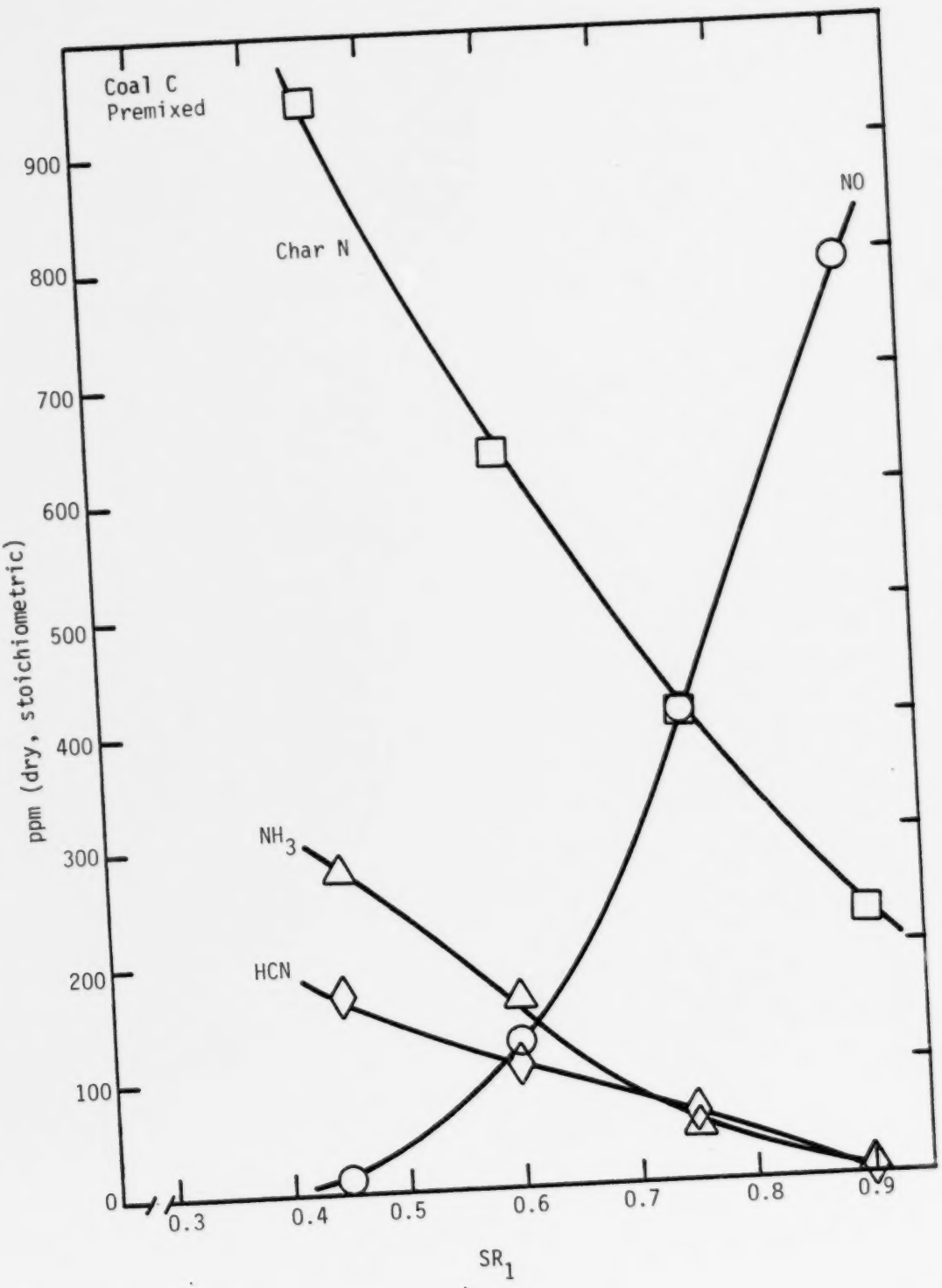

Coal U
Premixed
Staged @ 1.2 m
SR$_t$ = 1.25
NO, ppm (dry, 0% O$_2$)
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR$_1$

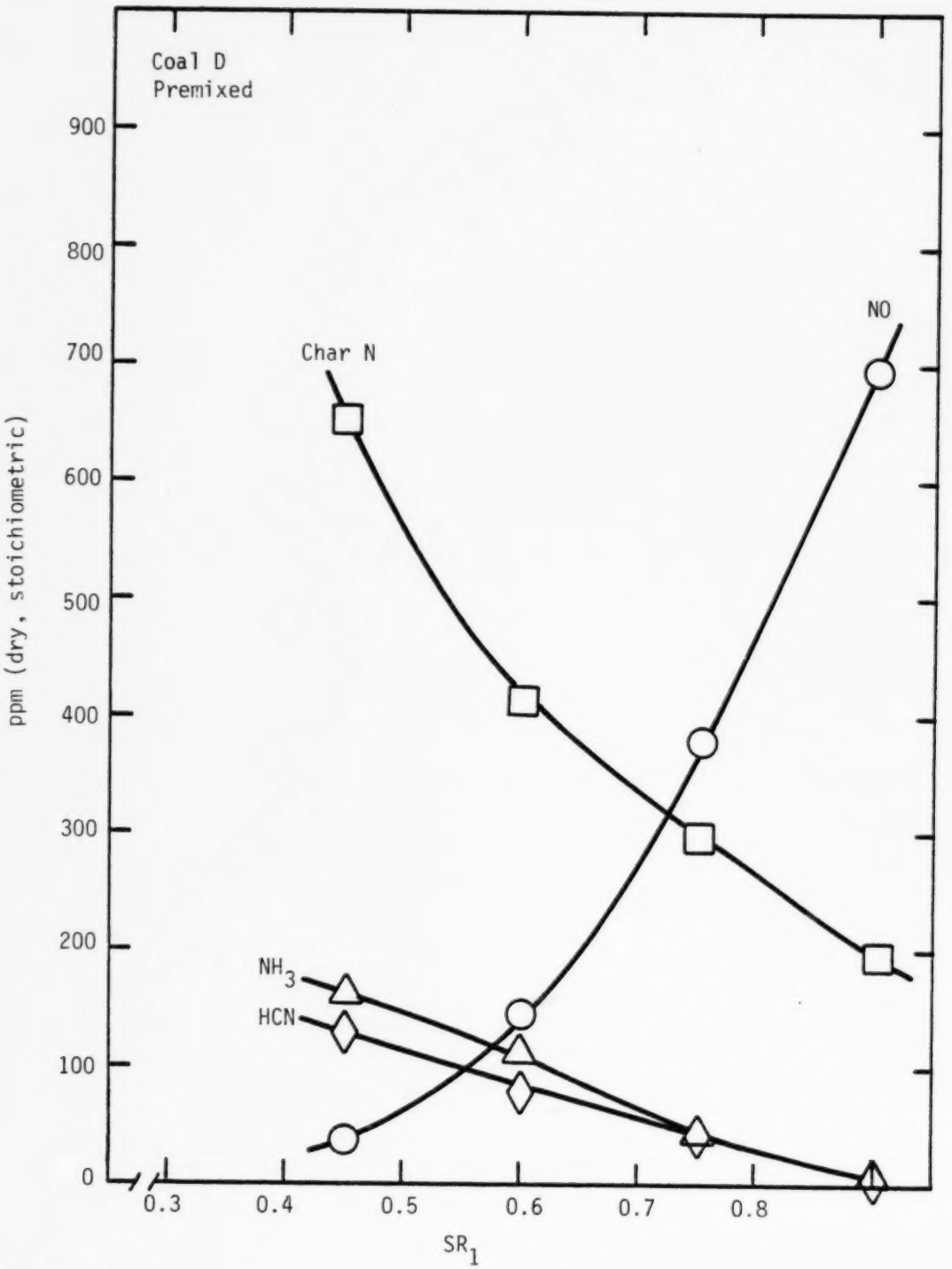
APPENDIX C

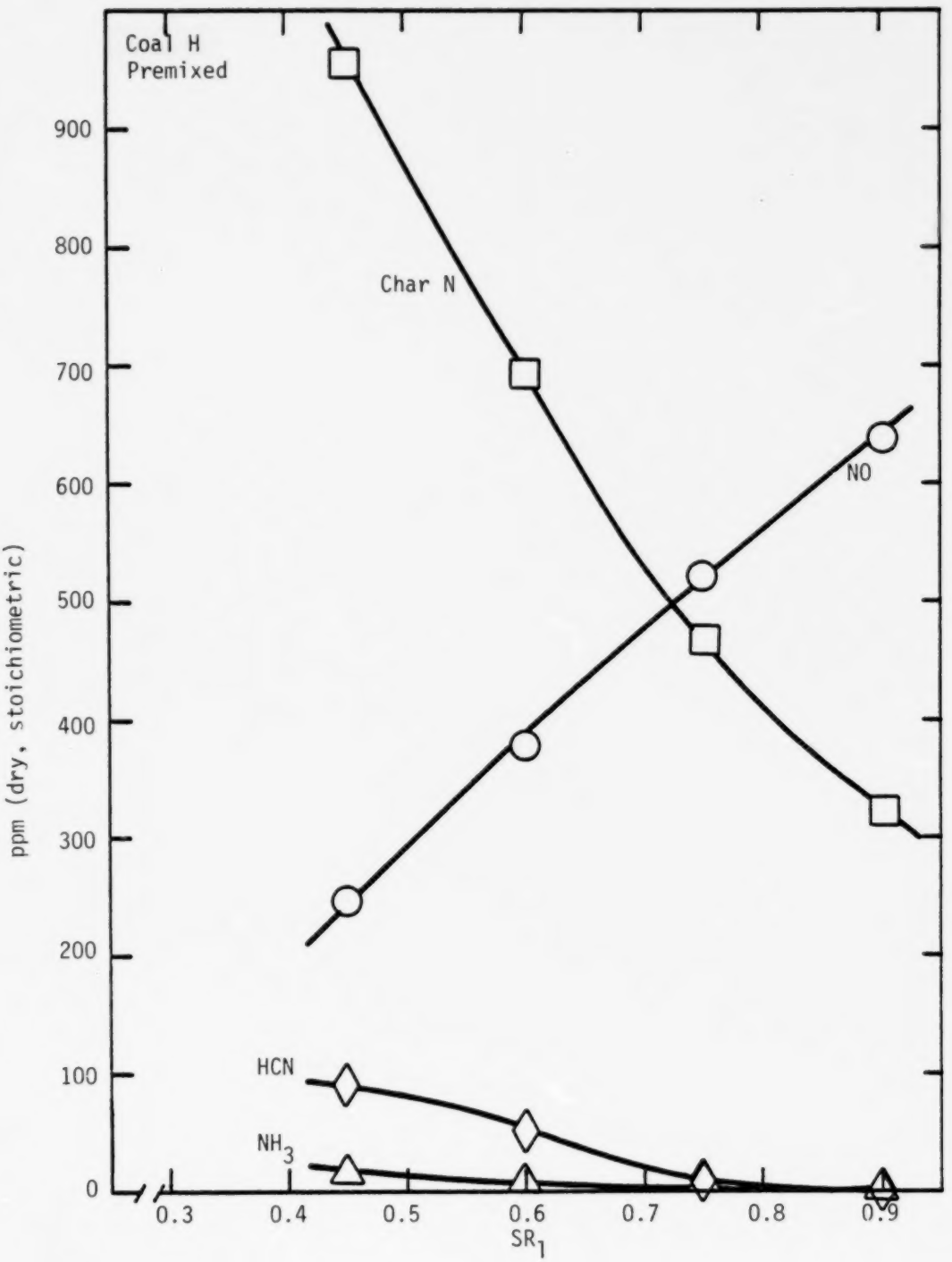
XN Species Concentrations and Char Nitrogen Retention at First-Stage Exit (normal)

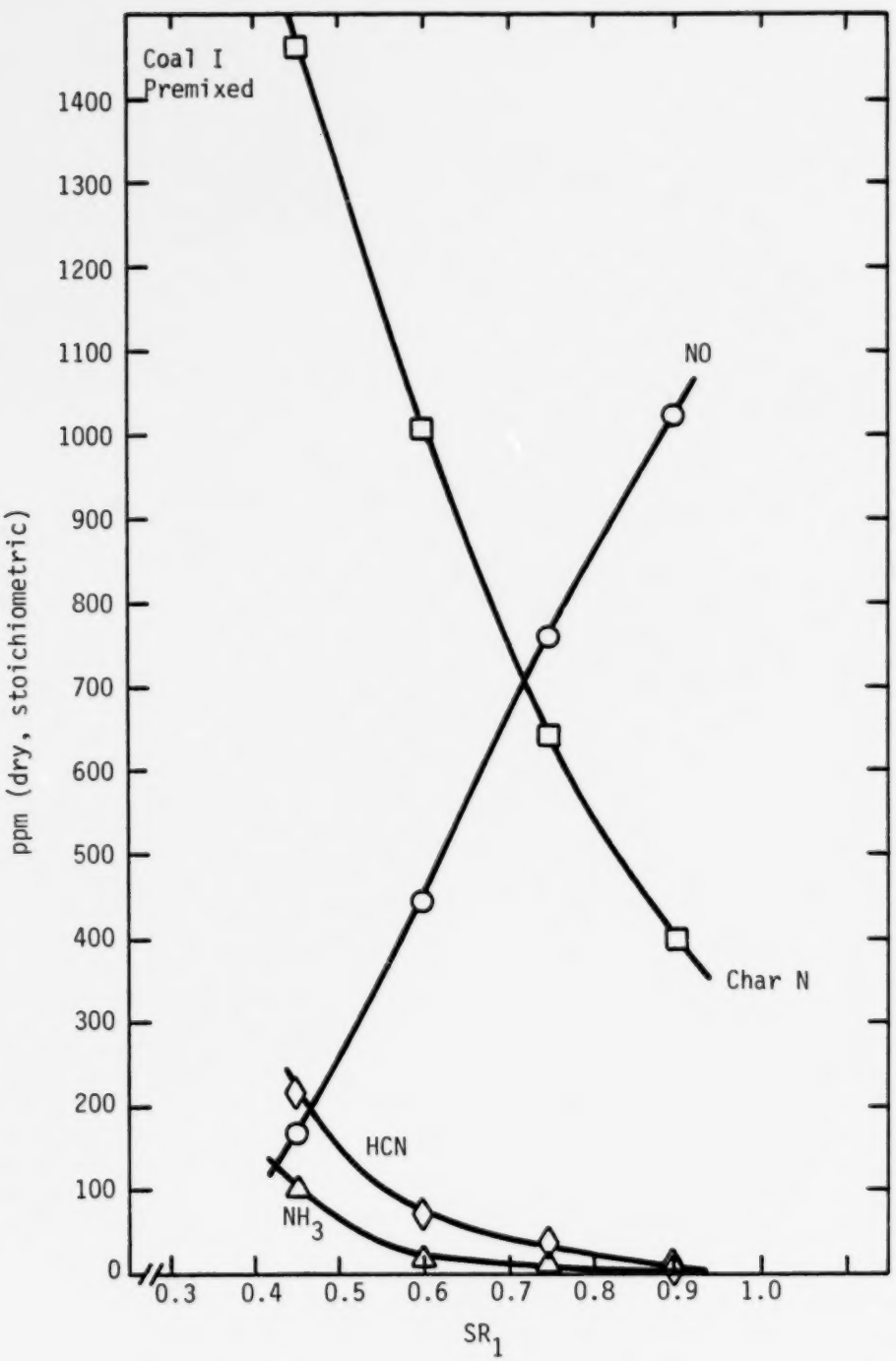


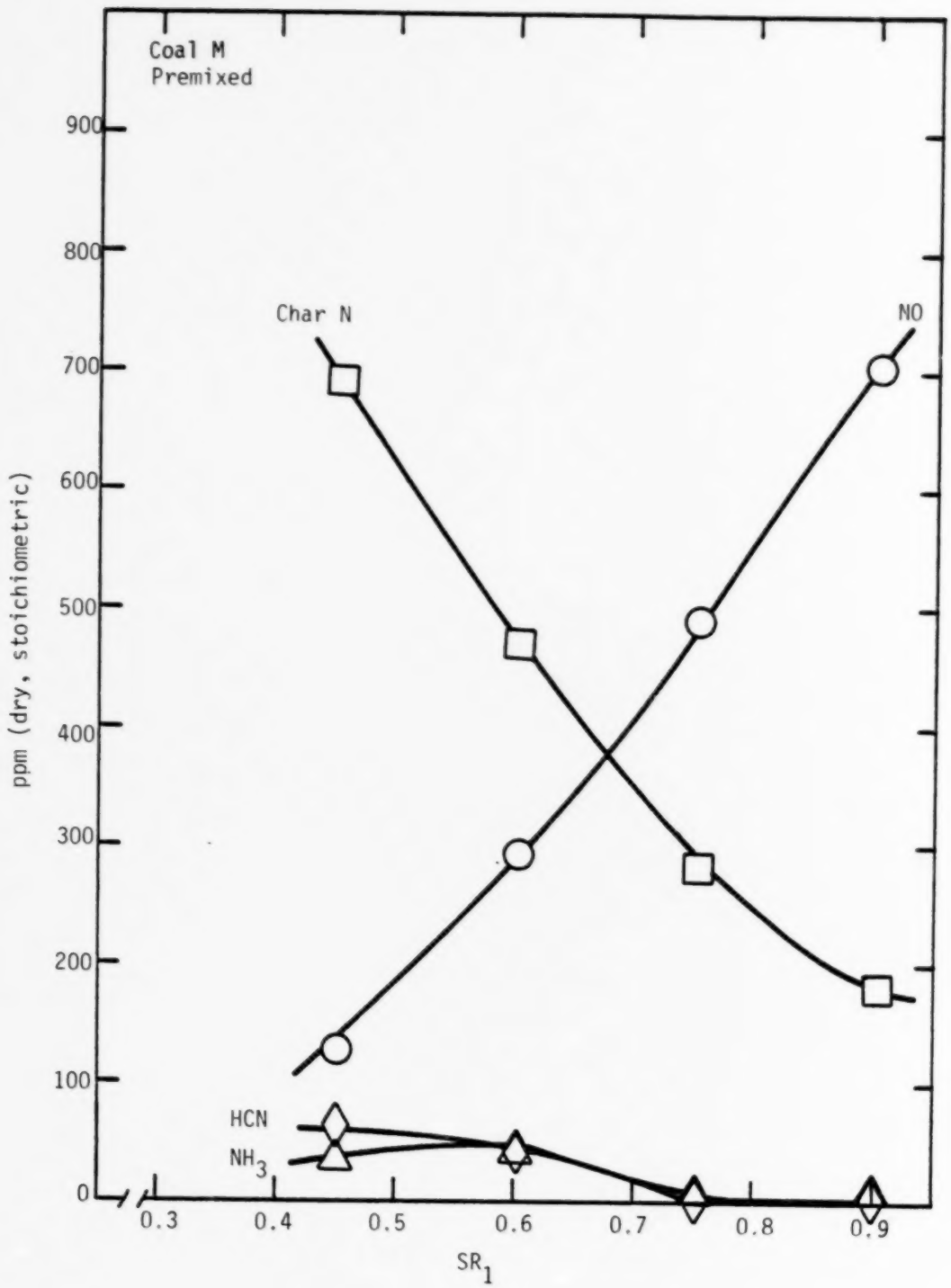

Coal A
Premixed
Char N
NO
NH3
HCN
ppm (dry, 0% O2)
SR1
1000
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9

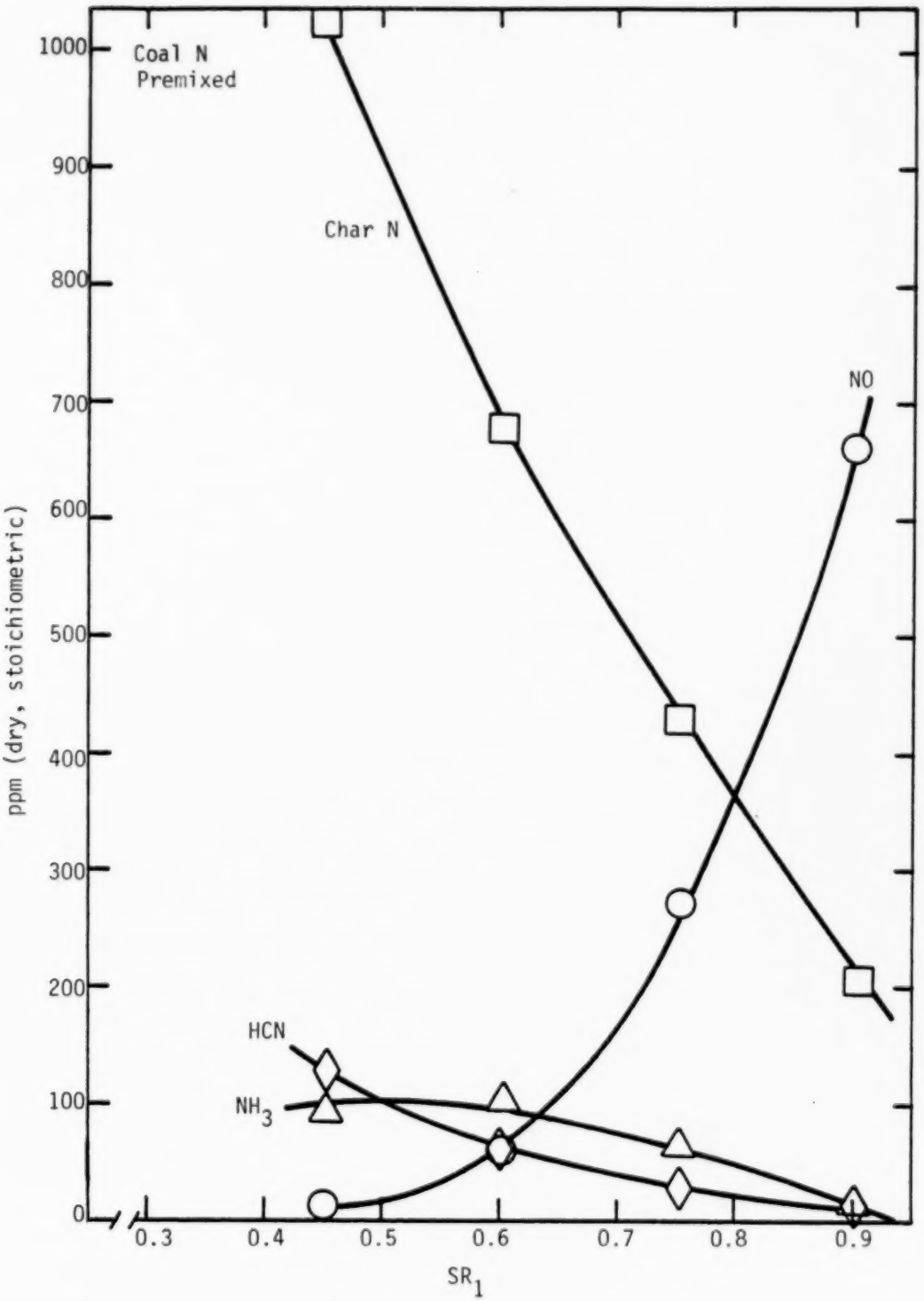

Coal C
Premixed
NO
Char N
NH3
HCN
ppm (dry, stoichiometric)
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR1

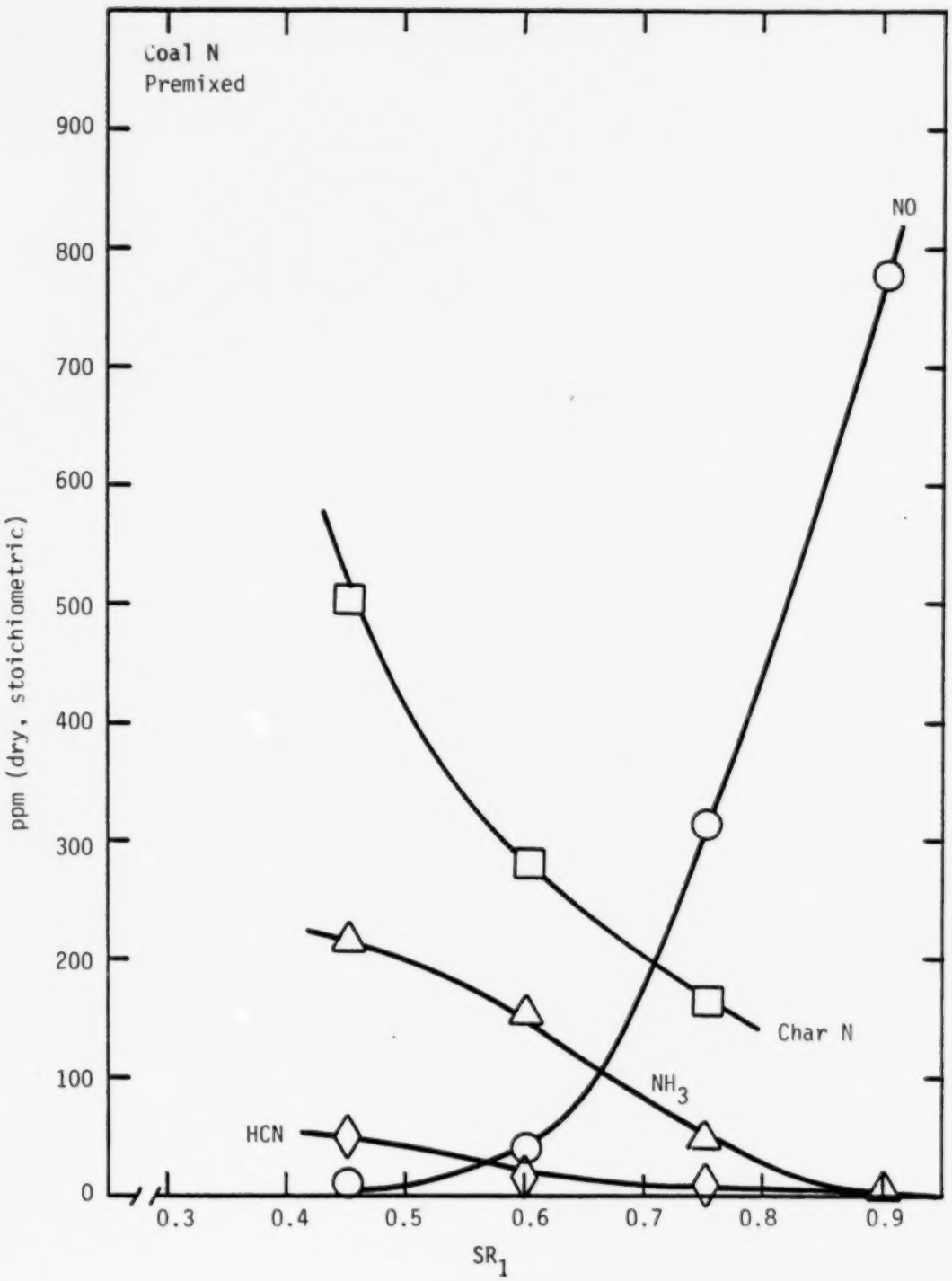

Coal D
Premixed
900
800
700
600
500
400
300
200
100
0
ppm (dry, stoichiometric)
Char N
NO
NH3
HCN
0.3
0.4
0.5
0.6
0.7
0.8
SR1

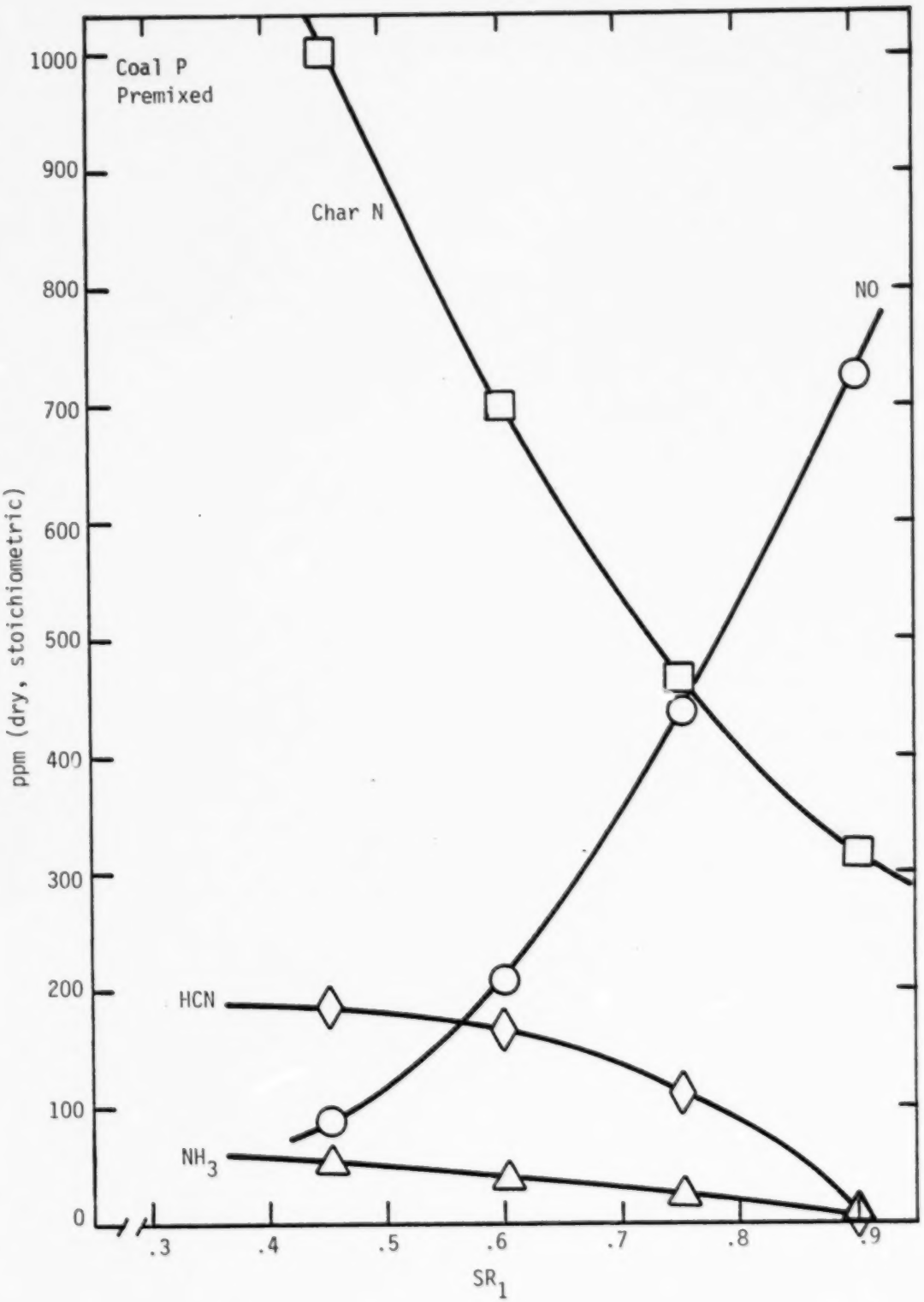

Coal H
Premixed
900
800
700
600
500
400
300
200
100
0
Char N
NO
HCN
NH_3
ppm (dry, stoichiometric)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1


Coal I
Premixed
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
ppm (dry, stoichiometric)
NO
Char N
HCN
NH3
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
SR1


Coal M
Premixed
900
800
700
600
500
400
300
200
100
0
ppm (dry, stoichiometric)
Char N
NO
HCN
NH3
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR1

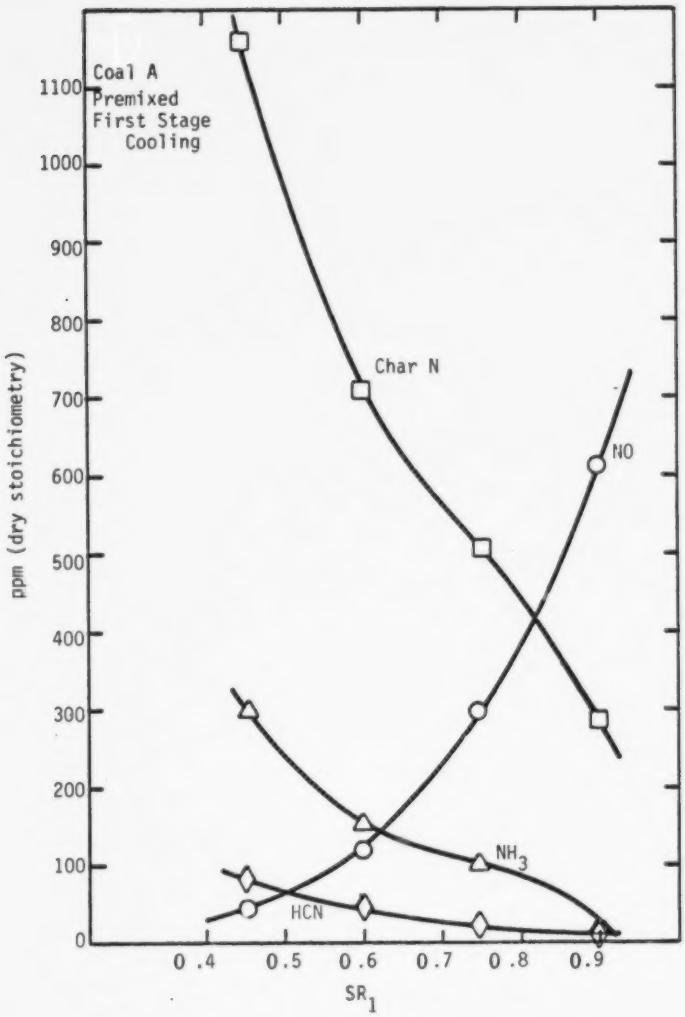

Coal N
Premixed
Char N
NO
HCN
NH_3
ppm (dry, stoichiometric)
1000
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1

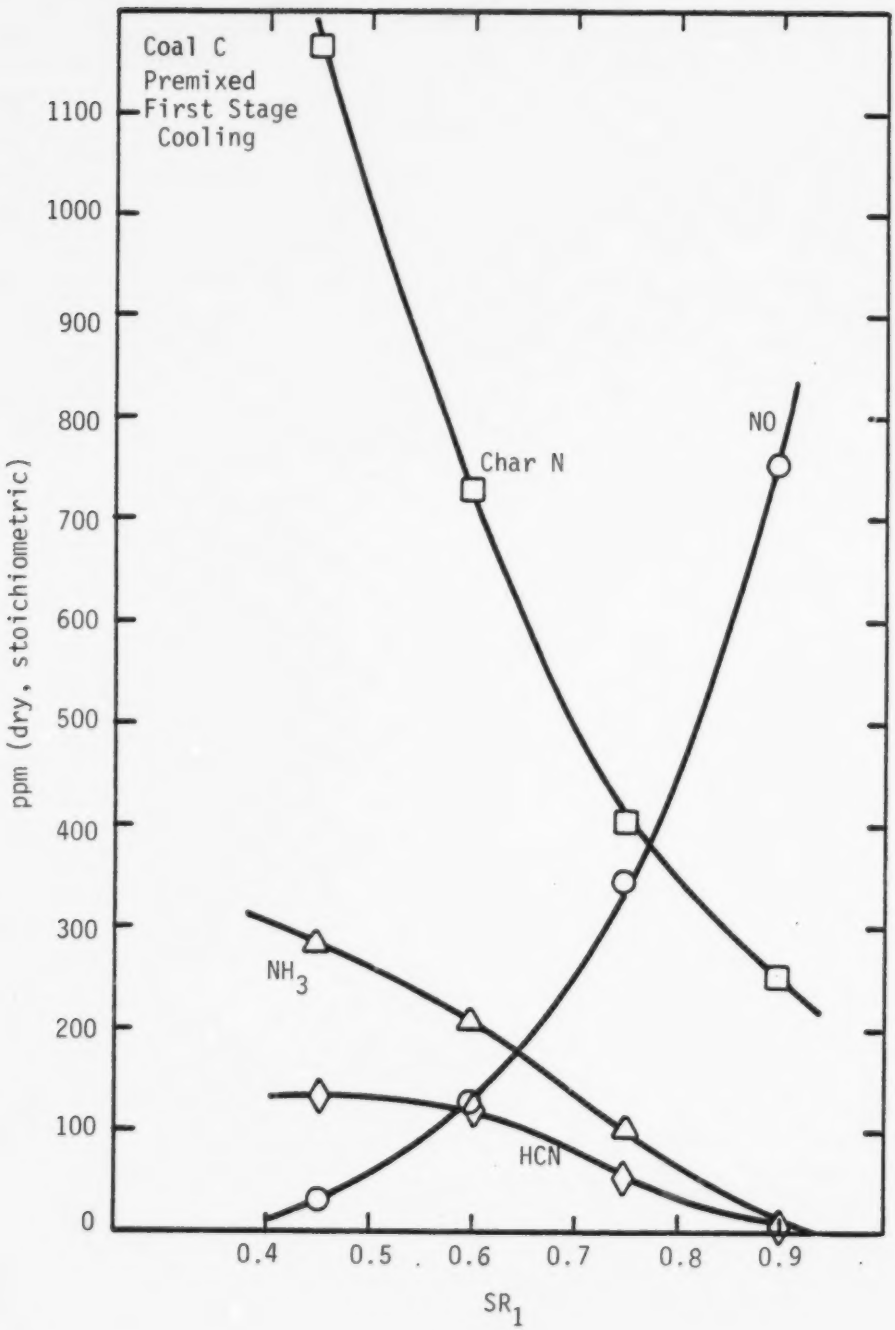

Coal N
Premixed
900
800
700
600
500
400
300
200
100
0
ppm (dry, stoichiometric)
NO
Char N
NH_3
HCN
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR_1

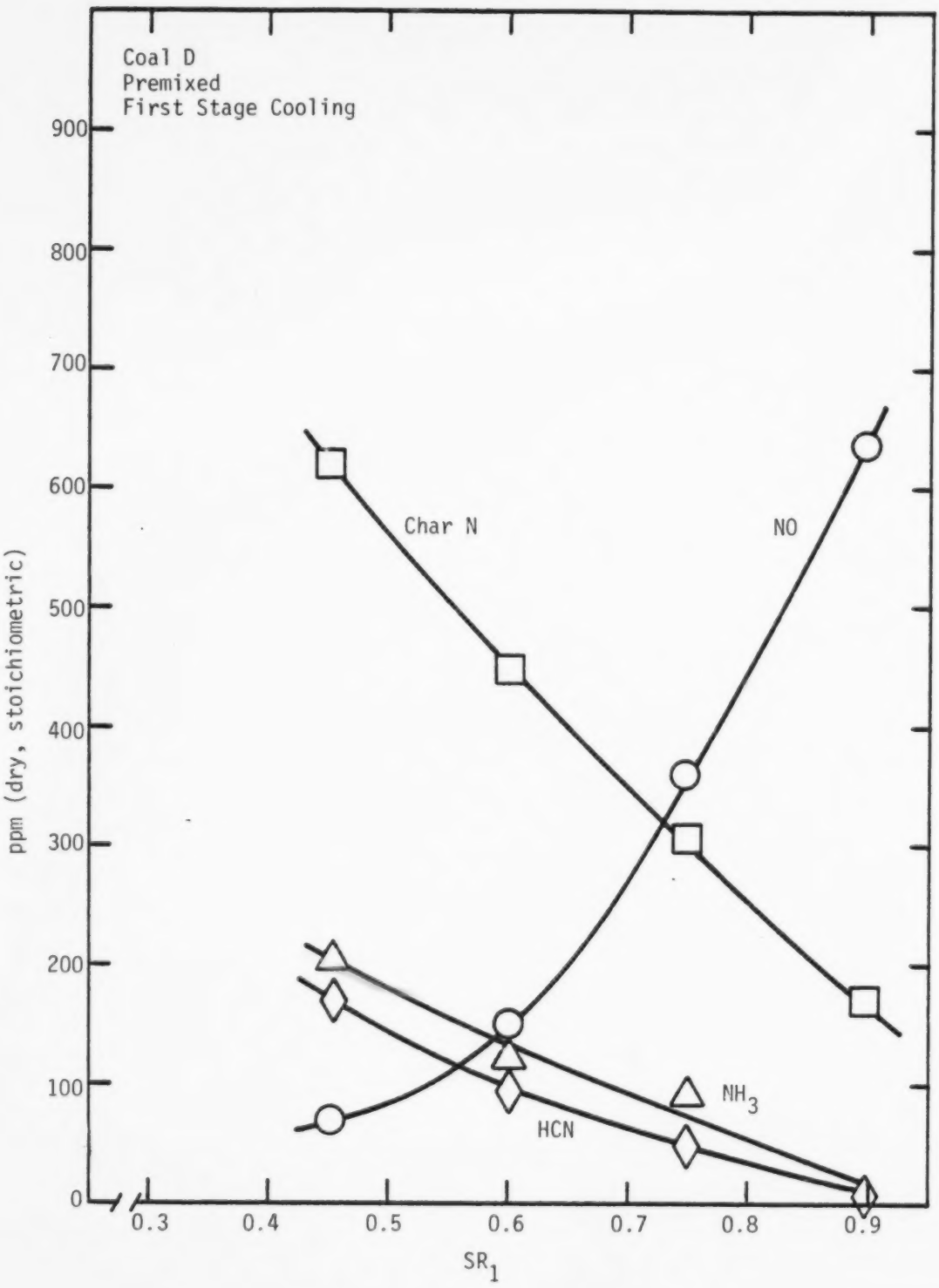

Coal P
Premixed
Char N
NO
HCN
NH_3
ppm (dry, stoichiometric)
1000
900
800
700
600
500
400
300
200
100
0
.3
.4
.5
.6
.7
.8
.9
SR_1

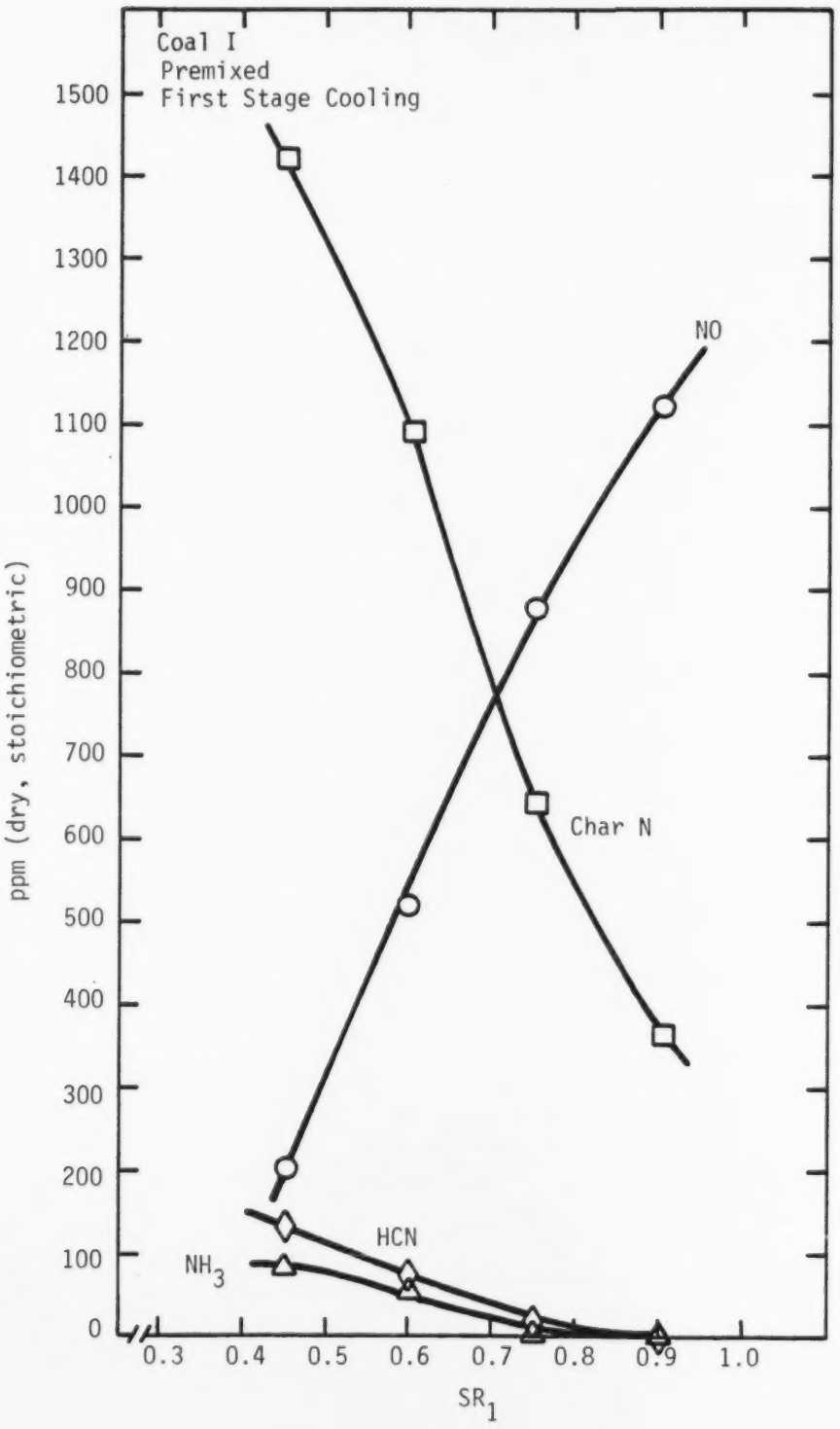
APPENDIX D

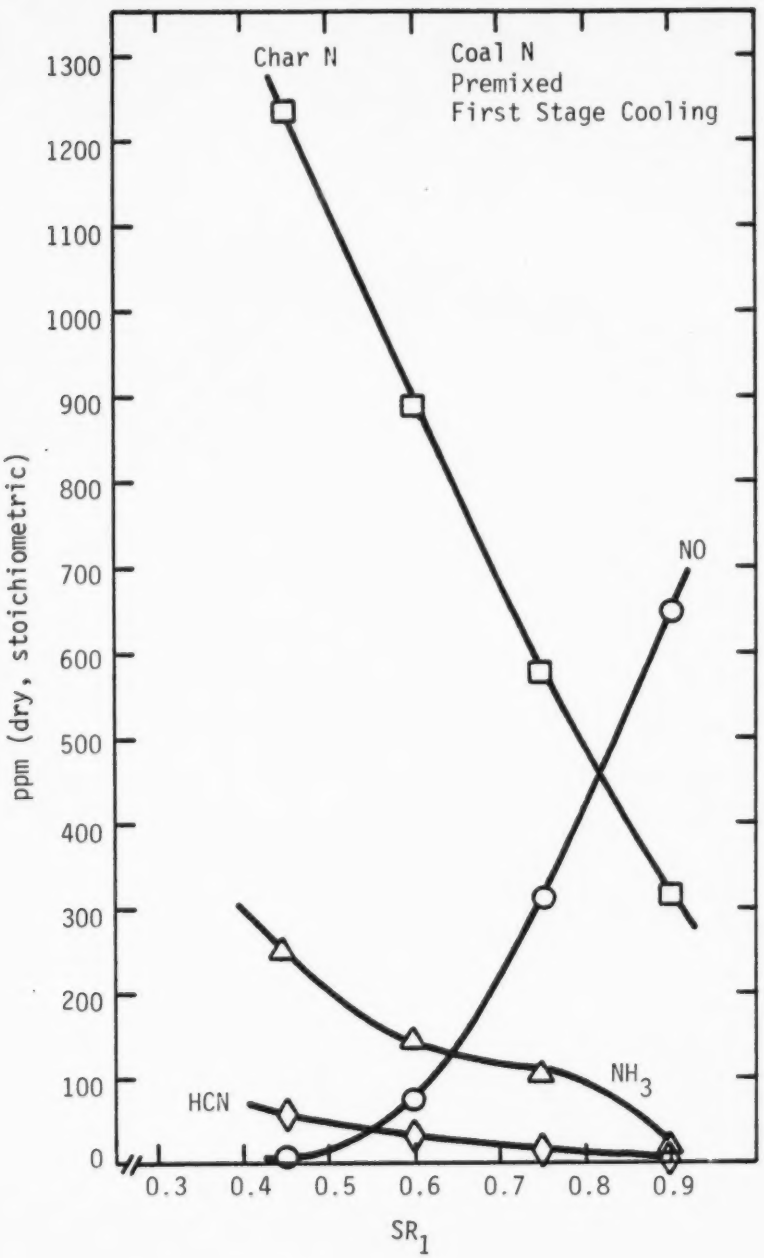
XN Species Concentrations and Char Nitrogen Retention
at First-Stage Exit (First-Stage Cooling)

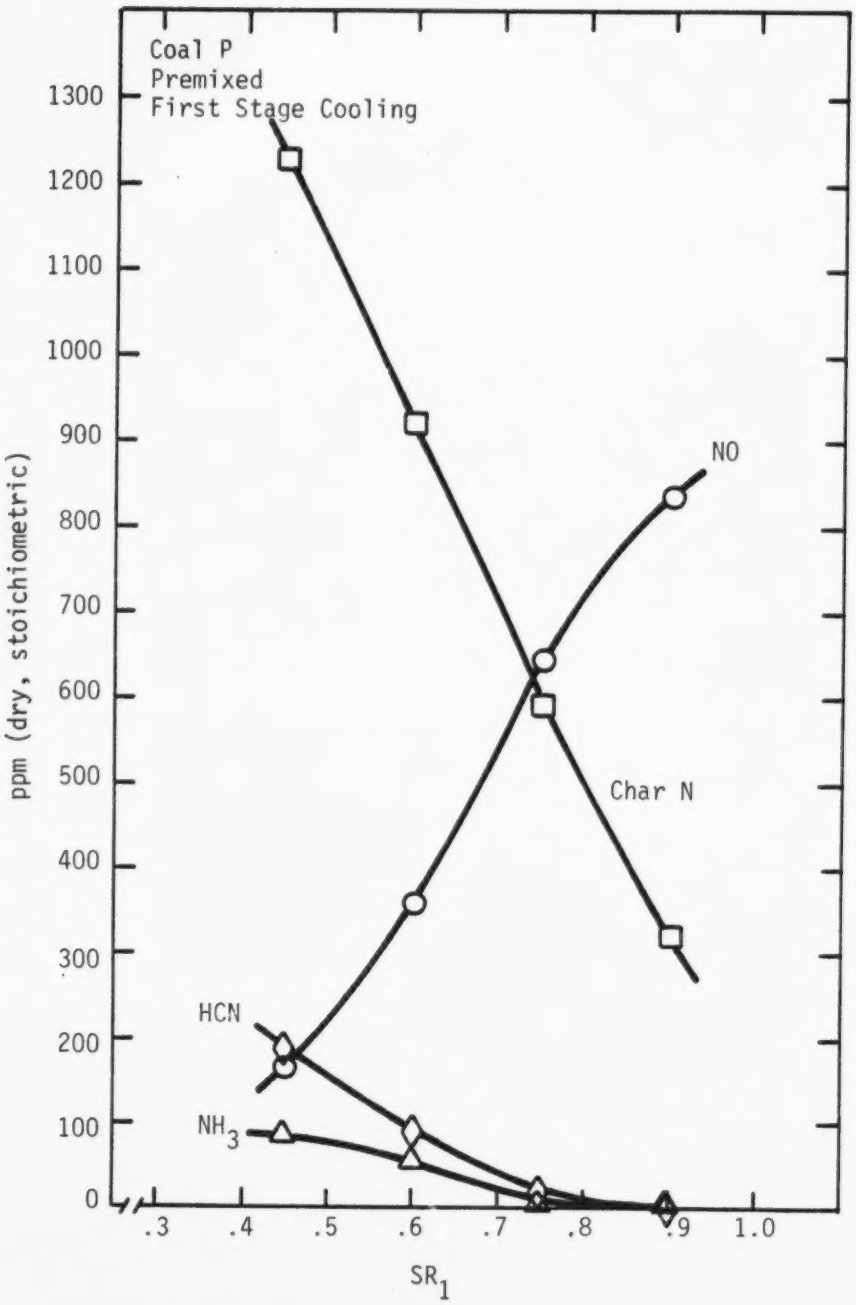



Coal C
Premixed
First Stage
Cooling
1100
1000
900
800
700
600
500
400
300
200
100
0
ppm (dry, stoichiometric)
Char N
NO
NH3
HCN
0.4
0.5
0.6
0.7
0.8
0.9
SR1


Coal D
Premixed
First Stage Cooling
900
800
700
600
500
400
300
200
100
0
ppm (dry, stoichiometric)
Char N
NO
NH3
HCN
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR1


Coal I
Premixed
First Stage Cooling
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
ppm (dry, stoichiometric)
NO
Char N
HCN
NH3
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
SR1


Char N
Coal N
Premixed
First Stage Cooling
NO
NH3
HCN
ppm (dry, stoichiometric)
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
SR1


Coal P
Premixed
First Stage Cooling
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
ppm (dry, stoichiometric)
NO
Char N
HCN
NH3
.3
.4
.5
.6
.7
.8
.9
1.0
SR1

Appendix E.

Analysis of U.S. Coals

Fuel Symbol													
Fuel Source	Hazellon PA.	Upper Cliff Alabama	Rosa Alabama	Black Creek Alabama	W. KY.	W. VA.	Elkay W. VA.	Gauley Eagle W. VA.	Price Utah	Price Utah	Utah (Coal)	Utah (Char)	Cadiz Ohio
Proximate Analysis (% as received)													
Moisture	5.13	3.00	8.02	2.25	5.43	7.57	0.60	3.72	6.39	7.41	4.20	2.70	4.29
Ash	5.74	9.49	6.79	4.45	7.53	12.05	11.61	26.89	7.40	8.83	9.62	16.83	18.05
Volatile Matter	4.39	20.44	21.81	28.28	37.79	29.12	33.35	26.65	38.89	38.84	42.97	10.29	34.87
Fixed Carbon	84.74	67.07	63.38	65.02	49.25	51.26	54.44	42.74	47.32	44.92	43.21	70.18	42.79
Ultimate Analysis (% Dry)													
C	88.45	79.32	81.23	82.12	71.58	74.68	73.96	59.43	73.17	72.24	69.36	75.39	62.08
H	2.14	4.47	4.73	5.21	5.43	4.96	4.93	4.11	5.55	5.75	5.32	1.28	4.44
N	0.79	1.47	1.54	1.79	1.55	1.38	1.39	1.35	1.54	1.55	1.50	1.22	1.07
S	0.47	1.30	1.04	0.75	3.21	0.86	2.47	0.84	0.66	0.76	1.04	1.12	7.40
Ash	6.05	9.78	7.38	4.56	7.96	13.04	11.69	27.94	7.90	9.54	10.05	17.30	18.86
O	2.10	3.66	4.08	5.56	10.27	5.08	5.56	6.33	11.18	10.16	12.73	3.69	6.15
Heating Value (Btu/lb, Wet)	13,124	13,254	13,394	14,284	12,082	12,228	13,115	10,110	12,340	11,877	11,718	11,185	11,038
CLASSIFICATION (ASTM D388)	Anthracite	Medium Volatile Bituminous	Medium Volatile Bituminous	Medium Volatile Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	High Volatile A Bituminous	High Volatile B Bituminous	High Volatile B Bituminous	High Volatile B Bituminous		High Volatile B Bituminous

Analysis of U.S. Coals (Cont'd)

Fuel Symbol	▽	◁	○	▽	◇	◁	◁	◇	○	□	△	◤
Fuel Source	Farmington N. M.	Four Corners N. M.	Fruitland N. M.	Colstrip Montana	Hardin Montana	Hardin Montana	Texas	Scranton N. D.	Beulah N. D.	Beulah N. D.	Savage Montana	Morwell Australia
Proximate Analysis (% as received)												
Moisture	7.76	5.24	11.02	21.27	22.70	20.49	25.23	34.96	33.10	34.63	36.36	9.07
Ash	17.96	24.06	20.72	9.58	11.26	8.62	10.28	7.50	7.12	4.97	4.61	3.38
Volatile Matter	34.95	35.94	31.66	30.82	31.26	33.24	35.31	28.85	28.65	27.02	28.48	48.79
Fixed Carbon	39.33	34.76	36.60	38.33	34.88	37.65	29.18	28.69	31.13	33.38	30.55	38.76
Ultimate Analysis (% Dry)												
C	63.06	55.99	58.71	67.52	65.54	67.88	60.99	64.61	65.29	66.15	64.99	66.25
H	4.65	4.71	4.21	4.36	4.15	4.65	4.49	4.17	3.96	4.20	4.04	5.01
N	1.40	1.23	1.30	1.38	0.95	0.99	1.13	0.83	0.99	0.96	1.00	0.65
S	0.81	1.03	0.93	0.63	0.79	1.07	1.02	1.52	1.14	0.37	0.42	0.28
Ash	19.47	25.39	23.29	12.17	14.57	10.84	13.74	11.53	10.64	7.60	7.25	3.72
O	10.61	11.65	11.56	13.94	14.00	14.57	18.63	17.34	17.98	20.72	22.30	24.09
Heating Value (Btu/lb, Wet)	10,391	9,425	9,344	9,169	8,603	9,229	8,131	6,446	7,245	7,254	6,995	10,051
CLASSIFICATION (ASTM D388)	High Volatile C Bituminous	High Volatile C Bituminous	High Volatile C Bituminous	Sub-Bituminous B	Sub-Bituminous B	Sub-Bituminous B	Sub-Bituminous C	Lignite A	Lignite A	Lignite A	Lignite A	